AMERICAN SOCIETY

OF

CIVIL ENGINEERS

THE DETERMINATION OF SAFE YIELD OF UNDERGROUND RESERVOIRS OF THE CLOSED-BASIN TYPE.

BY

CHARLES H. LEE, Assoc. M. Am. Soc. C. E.

WITH DISCUSSION BY

MESSRS. JAMES OWEN, G. E. P. SMITH, O. E. MEINZER,
KENNETH ALLEN, ROBERT E. HORTON,
AND CHARLES H. LEE.

Reprinted from *Transactions*, Vol. LXXVIII, p. 148 (1915).

AMERICAN SOCIETY OF CIVIL ENGINEERS

INSTITUTED 1852

TRANSACTIONS

Paper No. 1315

THE DETERMINATION OF SAFE YIELD OF UNDERGROUND RESERVOIRS OF THE CLOSED-BASIN TYPE.*

By Charles H. Lee, Assoc. M. Am. Soc. C. E.

With Discussion by Messrs. James Owen, G. E. P. Smith, O. E. Meinzer, Kenneth Allen, Robert E. Horton, and Charles H. Lee.

Synopsis and Conclusions.

The objects of this paper are to show the possibility and practicability of measuring the annual rate of recharge of underground reservoirs of the closed-basin type, and to indicate broadly the factors which determine safe yield from a basin by artificial development, such as Artesian flow or pumping.

The paper opens by pointing out the importance of the problem in California and the Southwest. Following this there is a description of the physical features of underground reservoirs and the general principles of inflow, outflow, and storage. The body of the paper presents detailed methods and results of extended measurements, by the Los Angeles Aqueduct Bureau and the United States Geological Survey, for the determination of the rate of annual recharge of the Independence Basin, in Owens Valley, California. The subjects of percolation from stream channels, relation of precipitation and altitude, soil evaporation combined with transpiration from grass, and ground-water fluctuations, were carefully studied in the field, and original data are pre-

* Presented at the meeting of May 6th, 1914.

sented. The paper closes with a discussion of the relation which the net safe yield from a basin bears to the rate of annual recharge.

The conclusions are as follows:

1.—The "underground reservoirs" of California and the Southwest are water-tight rock basins, represented by the topographic valleys, which are filled with porous alluvial material in which the voids are saturated with water.

2.—Inflow into these basins is by percolation from water on the surface of the alluvial filling, which source may occur as direct precipitation, stream flow, irrigation, or flooding. Natural ground-water loss occurs in the region of lowest depression of a basin, and consists of the breaking out of water at the surface in springs or seepages, evaporation from soil, transpiration, and underflow. Artificial development, by wells or other methods, reduces the natural ground-water loss. Considered as averages, the rates of recharge and ground-water loss are equal, unless the artificial draft is excessive.

3.—The rate of recharge in a region of small precipitation and high evaporation rate can be determined most accurately, and with least expenditure of time and money, by measuring the elements which make up the ground-water loss. Of the natural elements, the most important are soil evaporation and transpiration. The underflow is relatively small and often negligible.

4.—The safe yield of artificially developed ground-water obtainable from an underground reservoir is less than indicated by the rate of recharge, the quantity depending on the extent to which soil evaporation and transpiration can be eliminated from the region of ground-water outlet.

Introduction.

There are in California and the arid States of the Southwest many valleys underlaid by porous alluvial material in which the voids are filled with water. The ease with which water can be developed from wells in these valleys and the definite bounds of the water-bearing formation have led to the use of such terms as "underground lake," "underground basin", or "underground reservoir". These terms are in general use among local hydraulic engineers, and have been adopted by the California Courts in numerous recent decisions pertaining to the use of diffused percolating water occurring in closed basins.

A problem which is being presented to the Engineering Profession for solution is the determination of the safe yield of "underground reservoirs", or the net annual supply which may be developed by pumping and Artesian flow without persistent lowering of the ground-water plane. The answer to this problem must soon be had throughout the Southwest, and particularly in Southern California, where the use of underground water has advanced most rapidly. The available surface supplies of the region are now used so extensively that future extension of irrigation must depend on the underground supply. Already, however, the growing popularity of ground-water supply for irrigation and the heavy drafts made possible by improved pumping machinery and cheap power are giving rise to conditions of dangerous overdraft on many of the so-called inexhaustible underground water supplies. Furthermore, in many of the sparsely settled valleys of the Southwest, where very limited ground-water supplies are available, preparations are being made to develop pumped water for irrigation far in excess of the safe yield. The writer has in mind such a valley, where, out of 90 000 acres of agricultural land, filed on in good faith under the provisions of the Desert Land and Homestead Acts, it can be said with reasonable certainty that not more than 2% can ever be put under cultivation. In addition to the use of underground water for irrigation, it is being developed extensively for municipal purposes. The City of Los Angeles derives its present supply entirely from an underground reservoir, the San Fernando Valley, and is preparing to develop a similar supply in Owens Valley to be held as a reserve in connection with the Los Angeles Aqueduct. A portion of the supply of both Oakland and San Francisco is developed from underground sources, and the possibility of increasing largely the ground-water supply derived from Livermore Valley for the latter city has been the subject of considerable debate among prominent members of the Society. The problem, therefore, is an important one, and on it depends, not only the safe investment of capital, but also the very life of large industries and communities.

The sources of underground water are so difficult of measurement and its movements are so hidden from view, that the solution of the problem, until very recently, has been merely a subject for speculation and theory. Within the past few years, however, the study of underground water supply has been given considerable attention by the

United States Geological Survey as well as by engineers who have had these problems to meet. Although the fact of the existence of these "underground reservoirs" has been established, their sources of supply and outlets recognized, and many data regarding well fluctuations have been accumulated, yet very little has been done toward developing methods of measuring the rate of recharge or studying the factors which limit the quantity of water which can be safely developed from underground reservoirs.

The writer has had opportunity to investigate a number of the important underground reservoirs of California, and in this paper he presents certain general principles which seem to him to be justified by the existing data. Although these principles may seem to be self-evident, yet the writer has no knowledge that they have ever been applied to the practical solution of the problem in hand. To show the possibilities of their application, therefore, he presents data and studies for an underground reservoir in Owens Valley, California, where it was desired to ascertain the quantity of ground-water that could be developed safely without overdraft. Much of this information has already appeared in print* in greater detail, but the writer believes that the subject is of sufficient importance, and the component studies are of wide enough technical interest to be presented to the members of the Society for discussion and expression of opinion.

General Principles.

The typical underground reservoir is, geologically, a structural basin filled with alluvial débris from the adjoining mountain ranges. These basins are the product of faulting accompanied by the uptilting of a crustal block from one side of the line of fracture. The formation is very common throughout the Southwest, reaching its most perfect development in the Great Basin region of Utah and Nevada, where the name "Basin-Range" has been applied to it. In California the basins are found in the valleys of the Coast Range and along the base of the Sierra Nevada, Sierra Madre, San Bernardino, and San Jacinto Ranges. The rock enclosing these basins is in most cases impervious to water and practically insoluble. Along the coast of California, shales and cemented gravels predominate, and are practically non-water-bearing in comparison with the porous gravels

* Water Supply Paper No. 294, U. S. Geological Survey, 1912.

filling the basins; and, in the interior of the State, the enclosing rock formation is largely granite. Most of the basins can be considered as closed except for a subterranean outlet usually known as the "Narrows". This occurs at the lowest point in the rock rim, where the gravels contract into a neck filling a narrow depression or canyon cut into the confining rock. The quantity of underground water escaping through such an outlet is usually very small, however, as has been shown by a number of well-known underflow observations. Hence, the underground reservoirs can generally be considered as closed rock basins, the effective storage capacity of which is the void spaces between the particles of sand and gravel with which they are filled.

The usual sources of supply for underground reservoirs are percolation from flowing surface streams, from precipitation, or, where the supply is not ground-water derived from the basin, from irrigation on the surface of the porous gravels. The water thus absorbed sinks downward to the general ground-water plane and then moves laterally toward the region of lowest depression. This region, in contrast to the surrounding dry soil or desert, is usually characterized by springy, swampy conditions, and is commonly known in Southern California as a cienaga. The natural outlets for underground water are by springs or seepages discharging into the surface channels which drain the cienaga, by evaporation from damp soils and vegetation within the cienaga, and, to a limited extent, by underflow from the basin. The surface streams formed by the oozing out of underground water join to form a larger stream, which in all respects corresponds to the outlet of a lake or reservoir, and, passing from the basin, pursues its course just as any other surface stream. Its flow is characterized by permanence and regularity, except as it is augmented by surplus flood water which, during a limited period following winter storms, passes from the basin without being absorbed by the gravels.

The general principles of inflow into and outflow from an underground reservoir of the type described correspond with those of surface reservoirs. The difference lies in the relative speeds with which the general water surface assumes a horizontal position following increase or decrease of volume stored. In the case of a surface reservoir or lake, the effect of inflow or outflow is an immediate complete readjustment of surface level. The frictional resistance offered by the

particles filling an underground reservoir is so great, however, that the movement of water from an area of high level is very slow, varying from a few hundred feet to a few feet per day, depending on local conditions. As a result, the water surface in an underground reservoir is never horizontal, being steepest near the mouths of the mountain canyons, the run-off from which is the most important source of supply; it is most nearly horizontal at the region of outlet; and varies in slope and elevation from time to time, depending on the rate of recharge.

The average rates of inflow and outflow of an underground reservoir must be equal, otherwise there would be persistent rise or fall of ground-water levels until such a balance is reached. There are, therefore, two possible methods of measuring the rate of recharge, either by determining the total percolation from various sources into the porous material of the basin, or by determining the ground-water losses. The first method is to be preferred where the source of percolation is almost entirely stream flow from which channel losses can be accurately measured; or where the precipitation is large, well distributed through the year, and forms the principal source of supply. The first of these conditions could occur only in an arid region, and the second is typical of humid regions.

The method by determination of ground-water losses is one peculiarly adapted to arid or semi-arid conditions with high evaporation rate, such as exist throughout the Southwest. It has been the writer's observation in this region that soil evaporation and transpiration constitute from 50 to 100% of the ground-water losses from underground reservoirs, the average exceeding 75 per cent. Other losses are largely the flow from springs and seepages, which can be measured with precision. Rates of soil evaporation and transpiration from grasses do not present insurmountable difficulties of measurement under arid conditions. In fact, it has been the writer's experience that satisfactory results with specially designed equipment could be obtained from observations extending over 2 years, although a period of 3 years is preferable. Furthermore, the area from which evaporation occurs and the depth to ground-water at various points within it are not subject to wide fluctuations, and are easily measured. The determination of the rate of recharge of underground reservoirs of the basin type, therefore, is a problem of soil evaporation, transpiration, and stream

flow, all of which processes, with the exception of transpiration from trees, are now capable of measurement with relative accuracy at reasonable cost.

The general method pursued in the Owens Valley studies was to ascertain, by extended field measurements of soil evaporation, transpiration, and spring discharge, the average rate of outflow from the basin. All available evidence seemed to indicate that the basin was closed, so that the rate of outflow equalled the rate of inflow or recharge. As a check, therefore, the rate of inflow into this basin from precipitation, stream flow, and irrigation was also determined. The data are presented under the following headings: Physical Features, Precipitation, Stream Flow, Evaporation and Transpiration, Groundwater, and Rate of Recharge by Percolation.

Physical Features.

General.—The Owens Valley lies in east-central California, along the western border of the Great Basin, and at the base of the steep slope of the Sierra Nevada Mountains, as shown by Fig. 1. Including a northern extension, known as Long Valley, its length is 120 miles, and its width, from crest to crest of confining mountain ranges, varies from 15 to 40 miles. The total area of the valley and its tributary mountain drainage is about 3 300 sq. miles, of which 1 200 sq. miles are desert mountains from which the run-off is negligible, 536 sq. miles comprise the Sierra Nevada slope, which yields a large run-off, and 1 580 sq. miles are the transition slope and valley floor, from which very slight surface run-off occurs. The elevation of the valley floor varies from 8 000 to 3 570 ft. above sea level, the latter being at Owens Lake, the lowest depression of the valley. The average elevation of the crest of the Sierra Nevada is 12 500 ft., with many peaks exceeding this elevation by more than 1 500 ft. The White and Inyo Mountains, a desert range bordering the valley on the east, have an average elevation of 10 000 ft., with peaks reaching 13 000 ft.

The valley is a deep structural trough filled with porous alluvial material derived principally from the Sierra Nevada, and inclosed by impervious rock formations. The steep east face of the Sierra Nevada is the result of faulting accompanied by elevation and westward tilting of a great crusted block. The drainage system of the valley consists of a trunk stream, Owens River, fed by approximately

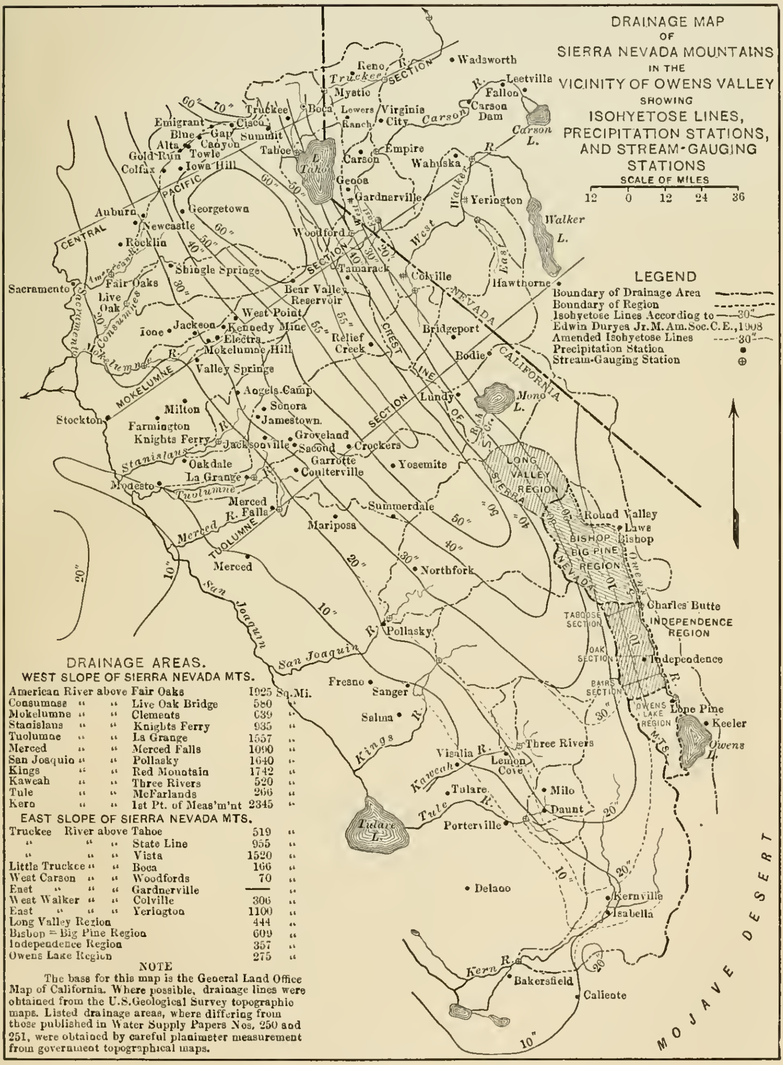

DRAINAGE MAP
OF
SIERRA NEVADA MOUNTAINS
IN THE
VICINITY OF OWENS VALLEY
SHOWING
ISOHYETOSE LINES,
PRECIPITATION STATIONS,
AND STREAM-GAUGING
STATIONS
SCALE OF MILES
12 0 12 24 36
LEGEND
Boundary of Drainage Area
Boundary of Region
Isohyetose Lines According to Edwin Duryea Jr. M. Am. Soc. C. E., 1908 30"
Amended Isohyetose Lines 30"
Precipitation Station
Stream-Gauging Station
DRAINAGE AREAS.
WEST SLOPE OF SIERRA NEVADA MTS.
American River above Fair Oaks 1925 Sq.Mi.
Consumnes " " Live Oak Bridge 580 "
Mokelumne " " Clements 639 "
Stanislaus " " Knights Ferry 935 "
Tuolumne " " La Grange 1557 "
Merced " " Merced Falls 1090 "
San Joaquin " " Pollasky 1640 "
Kings " " Red Mountain 1742 "
Kaweah " " Three Rivers 520 "
Tule " " McFarlands 266 "
Kern " " 1st Pt. of Meas'm'nt 2345 "
EAST SLOPE OF SIERRA NEVADA MTS.
Truckee River above Tahoe 519 "
" " " State Line 955 "
" " " Vista 1520 "
Little Truckee " " Boca 166 "
West Carson " " Woodfords 70 "
East " " " Gardnerville —— "
West Walker " " Colville 306 "
East " " " Yerington 1100 "
Long Valley Region 444 "
Bishop = Big Pine Region 609 "
Independence Region 357 "
Owens Lake Region 275 "
NOTE
The base for this map is the General Land Office Map of California. Where possible, drainage lines were obtained from the U.S. Geological Survey topographic maps. Listed drainage areas, where differing from those published in Water Supply Papers Nos. 250 and 251, were obtained by careful planimeter measurement from government topographical maps.
Reno
Wadsworth
Leetville
Fallon
Carson Dam
Carson L.
Walker L.
Yerington
Hawthorne
Mystic
Truckee
Boca
Virginia City
Carson
Empire
Wabuska
Tahoe
Genoa
Gardnerville
Woodford
Colville
Bridgeport
Bodie
Mono L.
Lundy
LONG VALLEY REGION
Round Valley
Laws
Bishop
BISHOP BIG PINE REGION
Charles Butte
INDEPENDENCE REGION
Independence
Lone Pine
Keeler
Owens L.
MOJAVE DESERT
Emigrant Gap
Cisco
Summit
Blue Canyon
Alta
Towle
Gold Run
Colfax
Iowa Hill
Auburn
Georgetown
Newcastle
Rocklin
CENTRAL PACIFIC
Sacramento
Fair Oaks
Live Oak
Shingle Springs
Tamarack
Bear Valley Reservoir
Ione
Jackson
West Point
Kennedy Mine
Electra
Mokelumne Hill
Relief Creek
Valley Springs
Angels Camp
Sonora
Jamestown
Stockton
Milton
Farmington
Knights Ferry
Jacksonville
Groveland
Second Garrotte
Crockers
Yosemite
Oakdale
La Grange
Coulterville
Modesto
Merced Falls
Summerdale
Mariposa
Merced
Northfork
Pollasky
San Joaquin R.
Fresno
Sanger
Selma
Kings R.
Three Rivers
Visalia
Lemon Cove
Tulare
Milo
Daunt
Porterville
Tulare L.
Delano
Kernville
Isabella
Bakersfield
Caliente
Kern R.

FIG. 1.

forty tributaries entering at fairly regular intervals from the west. The river terminates in Owens Lake, an alkaline body of water without outlet which disposes of all surplus surface water from the valley by evaporation. Irrigation is necessary for the production of crops, and water is diverted in canal systems from Owens River and tributary streams.

Independence Basin.—The portion of Owens Valley which is the subject of this study will be spoken of as the Independence Basin (Plate I). It lies in the south-central part of the valley, embracing with its tributary drainage area the region between the Sierra Nevada crest and Owens River, lying between Poverty Hills on the north and Alabama Hills on the south. These latter are secondary ranges extending into the valley from the Sierra Nevada and isolating a portion of the valley fill about 25 miles long and from 6 to 8 miles wide.

For the purpose of this study, the surface of the region has been classified as high mountain drainage, intermediate mountain slopes, outwash slope, and valley floor. (Table 1 and Plate I.)

TABLE 1.—SUBDIVISIONS OF INDEPENDENCE REGION.

Subdivision.	Area.		Boundary.		Slope.	Vegetation.	Character of surface.
	Square miles.	Percentage of total.	Upper.	Lower.			
High mountain drainage.	96.0	27	Sierra crest.	Mouth of canyon.	Precipitous to gentle.	Isolated forest trees.	Bare granite and fragmental rock accumulations.
Intermediate mountain slope.	29.4	8	Canyon drainage.	6 500 ft. contour.	2 000 to 3 000 ft. to the mile.	Desert bushes and nut pine.	Fragmental and finely disintegrated rock accumulations.
Outwash slope.	165.3	46	6 500-ft. contour.	Grass land.	300 to 600 ft. to the mile.	Desert bushes.	Boulders, sand and gravel
Valley floor:							
Cultivated....	4.7	1	....	....	Gentle.....	Alfalfa, etc....	Soil.
Meadow.......	45.1	13	....	....	Gentle to level.	Salt grass, etc.	Soil.
Alkali.........	2.7	1	....	....	Level......	None	Soil.
Desert........	13.9	4	....	....	Level......	Desert bushes.	Fine sand.
	357.1	100					

The high mountain drainage embraces the eastern slope of the Sierra Nevada and consists of a series of seventeen small canyons which are the drainage basins of streams tributary to Owens River (Table 2). These canyons are all narrow at the mouth (the 6 500-ft. level) and broaden out more or less toward the summit, presenting a roughly triangular shape. They are separated by high knife-edge ridges, which terminate in triangular slopes facing the valley. They have been cut by water erosion and sculptured by active glaciation above the 7 500-ft. level, their upper portions being well-developed glacial cirques. In many places below the cirques are series of benches occupied by glacial lakes or meadows. Most of the cirque floors are buried beneath morainal accumulations; some of the polished canyon bottoms between the 11 500 and 8 000-ft. levels are swept clean of débris, and others are completely buried by morainal material. Terminal and lateral moraines of considerable size occupy the canyon floors between the 8 000 and 7 000-ft. levels.

TABLE 2.—HIGH MOUNTAIN DRAINAGE AREAS OF INDEPENDENCE REGION.

Creek.	Area.		Elevation.		Shape.	Length of Sierra crest drained, in miles.	Remarks.
	Total, in square miles.	Percentage above 10 000 ft.	Head of canyon, in feet.	Mouth of canyon, in feet.			
Taboose	7.16	60	12 000	6 500	Triangular	3.34	Morainal deposits; regulated run-off.
Goodale	4.97	69	12 500	6 500	Triangular	2.67	Morainal deposits; regulated run-off.
Dry Canyon	2.48	65	12 000	6 500	Triangular	1.21	Morainal deposits; no surface run-off.
Division	3.88	51	12 000	6 000	Rectangular.	1.88	Morainal deposits.
Sawmill	7.64	44	12 000	5 000	Rectangular.	2.75	
Thibaut (N. Fk.)	2.25	20	11 500	6 000	Irregular	0.0	
Thibaut (S. Fk.)	2.62	55	12 000	6 000	Irregular	0.0	
Oak (N. Fk.)	8.08	65	12 500	6 000	Irregular	5.17	Morainal deposits; regulated run-off.
Oak (S. Fk)	7.28	57	12 500	6 000	Irregular	1.06	
Little Pine	8.42	74	13 000	6 500	Triangular	4.60	
Pinyon	4.29	47	13 000	6 500	Irregular	1.09	
Symmes	4.22	43	13 000	6 300	Triangular	1.59	
Shepard	12.29	66	13 500	6 500	Triangular	7.95	5.68 miles of crest south of Kings-Kern divide.
Bairs (N. Fk.)	4.01	43	13 500	6 300	Irregular	0.0	Lies on east face of Mount Williamson.
Bairs (S. Fk.)	2.90	41	13 000	6 300	Irregular	0.0	Lies on east face of Mount Williamson.
George	9.10	74	13 500	6 500	Triangular	3.89	
Hogback	4.38	58	13 000	7 000	Irregular	0.67	
	95.97	55	......	......	....	37.87	

The intermediate mountain slopes (Fig. 2) are the triangular areas terminating the ridges between the canyons, and probably represent the original face of the range before it had been actively eroded (Table 3). Their lower boundary has been arbitrarily placed at the 6 500-ft. contour, and their apexes reach a maximum elevation of about 12 000 ft. They have a steep uniform slope of from 2 000 to 3 000 ft. to the mile, and in general are covered with a mantle of disintegrated rock and slide material which merges into the valley fill.

TABLE 3.—INTERMEDIATE MOUNTAIN SLOPES OF INDEPENDENCE REGION.

Adjoining high mountain drainage areas.	Area, in square miles.	Elevation.			Distance from Sierra crest to center of area, in miles.	Remarks.
		Apex, in feet.	Center of area, in feet.	Lower border, in feet.		
Tinemaha	2.17	(11 000)	8 000	6 500	3.0	
Red Mountain	2.37	(12 000)	8 300	6 500	3.0	
Taboose	3.94	12 200	8 000	6 500	3.3	
Goodale	2.29	11 800	7 200	6 500	2.6	Does not include Dry Canyon.
Division	0.95	9 500	7 500	6 500	3.5	
Sawmill	1.32	10 200	7 500	6 500	3.2	
Thibaut (North Fork)	0.53	10 500	7 500	6 500	3.1	
Thibaut (South Fork)	0.07	7 000	6 700	6 500	4.0	Charlies Canyon yields run-off in normal and above normal years.
Oak (North Fork)	3.62	12 600	7 100	6 500	4.2	
Oak (South Fork)	1.03	10 600	7 100	6 500	3.8	
Little Pine	2.02	11 800	7 400	6 500	3.8	Lime Fork yields run-off in normal and above normal years.
Pinyon	2.89	11 500	7 600	6 500	2.7	
Symmes	0.42	9 200	7 400	6 500	3.2	North Fork similar to Lime Fork.
Shepard	0.97	9 900	7 200	6 500	4.5	
Bairs (North Fork)	0.48	9 100	7 100	6 500	5.0	
Bairs (South Fork)	1.21	10 300	7 800	6 500	4.6	
George	2.09	11 200	8 100	6 500	3.5	
Hogback (one-half)	1.08	10 800	7 900	6 500	4.1	
	29.45	....	....	....	....	

The outwash slope (Fig. 2) is the desert portion of the surface of the valley fill, extending from the 6 500-ft. contour at the base of the Sierra Nevada to the upper edge of grass and irrigated land in the valley (3 900 to 4 000 ft.). Its surface is composed of loose boulders, gravel. and sand, deposited during past ages by torrential streams coming from the mountains. This deposit is of

FIG. 2.—EASTERN SLOPE, SIERRA NEVADA.

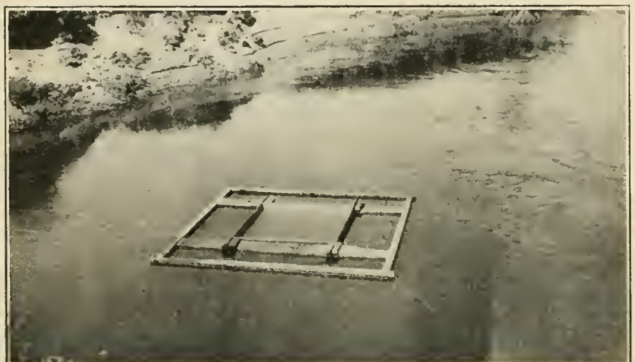


FIG. 3.—EVAPORATION PAN IN OWENS RIVER.

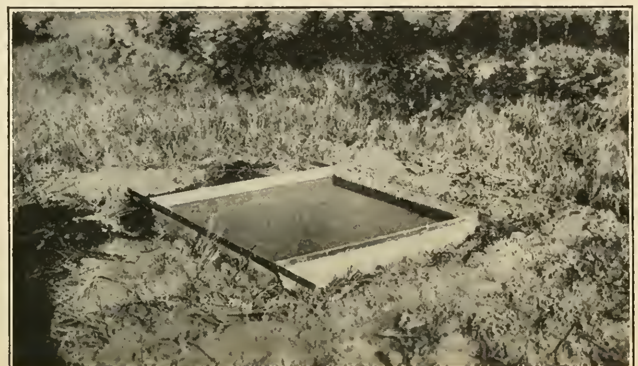


FIG. 4.—EVAPORATION PAN IN SOIL.

unknown depth, and lies on a buried ancient rocky surface, the higher hills of which appear above the present surface as buttes or knolls. The channels of streams draining the mountain canyons cross this slope in trenches, which, near the mountains, are from 25 to 50 ft. deep.

The valley floor embraces the area between the outwash slope and Owens River, and its surface may be classified as irrigated land, grass or meadow land, alkali land, and desert. The upper edge has a maximum slope of about 120 ft. to the mile, but within a short distance it merges into the practically level valley. The surface is soil to a depth of from 1 to 3 ft., except on the desert land, where it is fine sand. Most of the irrigated land is along the upper margin of the valley floor adjoining the creek channels. The grass or meadow lands lie between and to the east of the ranches, and extend well out into the level valley. The growth is most luxuriant in the spring zone, which is about ¼ mile wide and is at the upper edge of the valley floor. Here are numerous small flowing springs, with temperature of about 62°, which start the meadow grass early in the season and keep it green until late in the autumn. Farther out in the valley, the salt grass makes a green carpet from May until late July. In the salt-grass land there is always a deposit of alkali about the plant roots, and the soil surface is crusted. The spring zone, however, is free from alkali. The worst alkali land is practically bare of vegetation and is thickly crusted with white salts. It lies in the more level areas in the center of the valley.

The desert area to the east of Owens River yields no appreciable run-off, and, owing to its light precipitation, it makes no contribution to the ground-water.

The alluvial material which forms the valley fill varies in size from large boulders to fine clay, and, in arrangement, from a thorough mixture of all sizes to layers of well-assorted gravel, sand, and clay. The transporting medium was water, both mountain streams and Owens River taking part in the work. Some of the material was deposited in the beds and on the sides of shifting stream channels, and much of the finer sand and clay was deposited from the quiet waters of a large lake which occupied the lower portion of the valley. The structure of the valley fill, therefore, is complex, and the character of the alluvial material underlying a given locality is difficult to determine without actual examination from borings.

A number of borings, ranging in depth from 250 to 500 ft., have been made in the basin by the City of Los Angeles, in connection with the development of the aqueduct supply. In general, the materials encountered were clay, sand, and coarse gravel in layers varying in thickness from a few inches to 150 ft. Coarse material in thin layers interbedded with clay predominates along the upper edge of the valley floor in the spring belt. All wells in this belt yield Artesian flows of from 1 to 2 sec-ft. The material is progressively finer and occurs in thicker strata east of this belt, toward the center of the valley, and the Artesian flows decrease in volume. Near Owens River, fine sand and clay in alternate layers is the only material encountered above the 300-ft. depth.

The streams from the Sierra Nevada were by far the most active in the work of building up the valley fill. Their loads were acquired in the mountain canyons and carried out into the valley, where they were dropped in order of size as the velocity of flow decreased. The old lake level stood at an elevation of about 3 790 ft. for a long period, as shown by beach lines on the east slope of the Alabama Hills. The present 3 790-ft. contour lies near the spring and Artesian belt. The finer materials between the spring belt and Owens River are evidently lake deposits. The ancient lake was contemporaneous with other geologic lakes of the Great Basin, such as Lakes Bonneville and Lahontan. The geologic history of these lakes shows many wide fluctuations of water level, covering long periods of time. The interbedding of fine and coarse material encountered in the spring belt is evidently the result of such fluctuation, as the sudden checking of the velocity of a stream on entering a body of still water results in the immediate deposition of coarse material. The Artesian and spring conditions, therefore, result from hydrostatic pressure on the water entrapped in these wedges of coarse material.

Two cross-sections of the valley, showing the probable geologic structure, were constructed along the Thibaut and Independence Sections (Fig. 5). The topography for these sections was obtained from the U. S. Geological Survey's map of the Mount Whitney quadrangle, and the character of the surface material was determined by field inspection. The exposed slopes of bed-rock on each side of the valley were joined beneath the valley floor, and the arrangement of the material filling the basin thus formed was represented according to

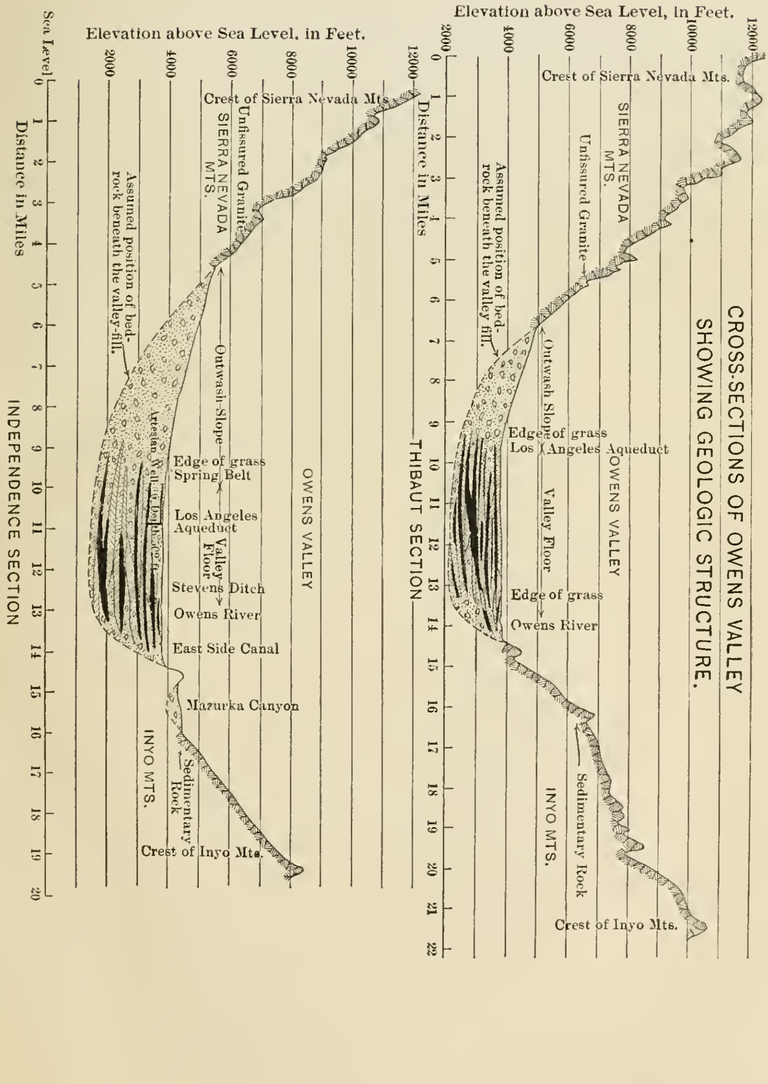

CROSS-SECTIONS OF OWENS VALLEY
SHOWING GEOLOGIC STRUCTURE.
Elevation above Sea Level, in Feet.
Crest of Sierra Nevada Mts.
SIERRA NEVADA MTS.
Unfissured Granite
Assumed position of bed-rock beneath the valley fill.
Outwash Slope
Edge of grass
Los Angeles Aqueduct
OWENS VALLEY
Valley Floor
Edge of grass
Owens River
INYO MTS.
Sedimentary Rock
Crest of Inyo Mts.
Distance in Miles
THIBAUT SECTION
Elevation above Sea Level, in Feet.
Sea Level
Crest of Sierra Nevada Mts.
Unfissured Granite
SIERRA NEVADA MTS.
Assumed position of bed-rock beneath the valley-fill.
Outwash Slope
Edge of grass Spring Belt
Los Angeles Aqueduct
Valley Floor
Stevens Ditch
Owens River
East Side Canal
OWENS VALLEY
Mazurka Canyon
INYO MTS.
Sedimentary Rock
Crest of Inyo Mts.
Distance in Miles
INDEPENDENCE SECTION

Fig. 5.

the best available knowledge, the strata of fine material being indicated by solid black. On the diagram, the greatest depth of alluvial filling measures 2 500 ft. in the Independence Section, and 1 800 ft. in the Thibaut Section. Two of the aqueduct wells near the Independence Section reached depths of 500 ft. in alluvial material, and a well drilled by the Southern Pacific Company, opposite the Alabama Hills at Lone Pine Station has reached a depth of 832 ft., entirely in fine sand. There is no reason to suppose that the gravel filling near Independence is less than 2 000 ft. in depth.

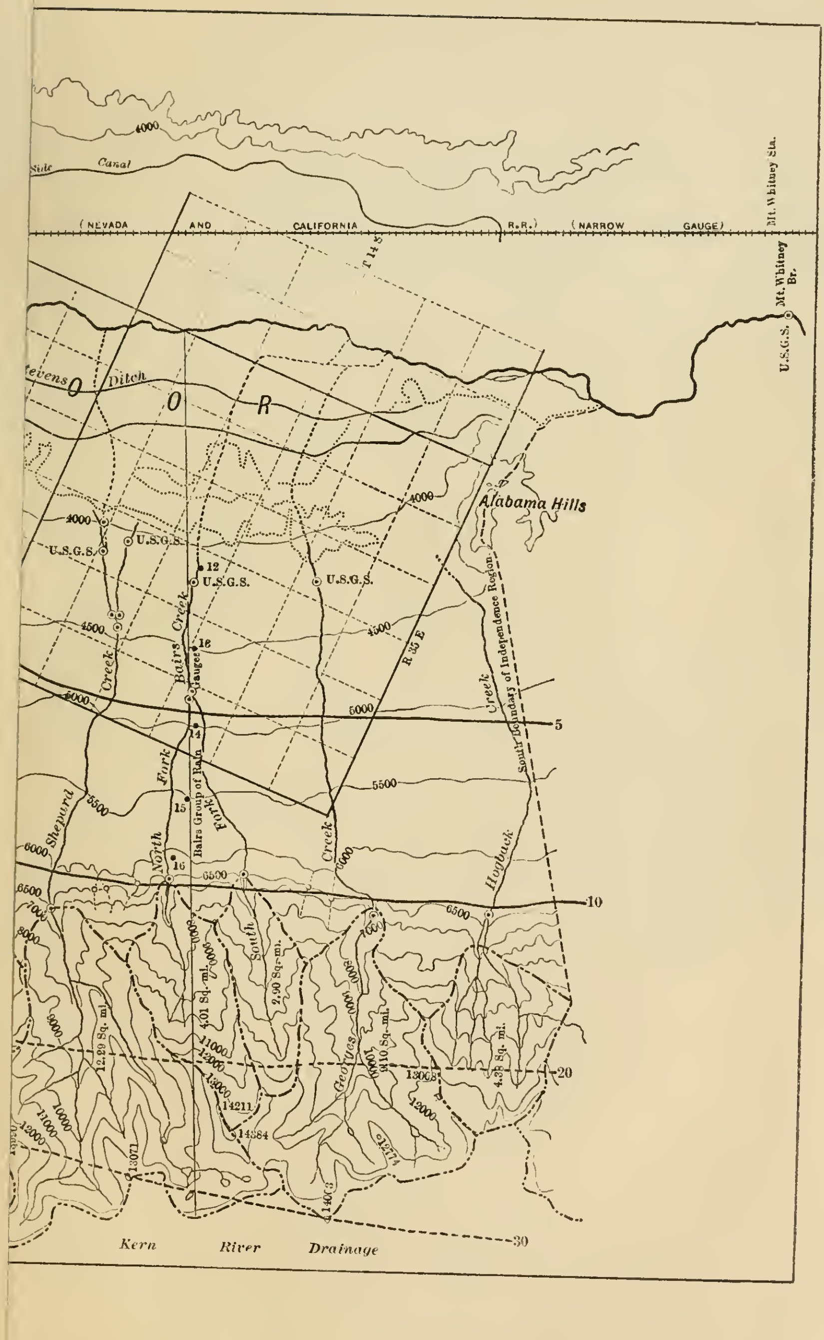
The volume of void space, or porosity, of a body of alluvial material of this type is variously estimated by different authorities at from 20 to 35% of the total. Samples of the mixed gravel, sand, and silt of the outwash slopes west of Independence were removed to a depth of 4 ft., without disturbing the natural arrangement of the particles, and weighed dry and after saturation. The results of these tests indicate a porosity of 28% for these samples. The presence of very coarse gravel and boulders in this material would reduce the porosity, and, for the valley fill as a whole, 25% is probably more nearly correct.

Precipitation.

The plan followed in the study of precipitation was to gather and assemble data from which to prepare isohyets for the basin. These appear on Plate I, and are based on the available precipitation data and an intimate knowledge of the local topography and vegetation.

Observations of precipitation were made in the Independence Basin as early as 1865, under the direction of United States Army officers stationed at Fort Independence. The record extends unbroken from September, 1866, to August, 1877, and was obtained under conditions sufficiently similar to permit of combining it with the more recent Weather Bureau record at Independence. The latter covers the periods from September, 1892, to August, 1895, and from September, 1898, to August, 1910, so that there are 26 seasons for which precipitation records are available at Independence. To supplement this record, twenty standard Weather Bureau rain gauges were established, and observations were made during the seasons 1908-09 and 1909-10 (Plate I). These gauges were distributed systematically over the valley floor and outwash slopes, and could all be reached during one day by three mounted observers stationed at points

PLATE I.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.



MAP OF INDEPENDENCE REGION
SHOWING
DRAINAGE AREAS, STREAM CHANNELS
AND PRECIPITATION STATIONS.

in the valley where shelter was available. Four records were also available in Owens Valley, outside of the Independence Basin, at Bishop, Lone Pine, Laws, and Keeler. The Bishop and Lone Pine records are kept by co-operative Weather Bureau observers, and cover 15 and 5 years, respectively. The Laws and Keeler records are kept by railroad agents, and are for 13 and 24 years.

The distribution of total precipitation, with respect to geographic location, in the Independence Basin and adjoining areas depends to a great extent on topographic features, notably mountain ranges and valleys, although a consistent variation is also evident with changes in latitude. The controlling topographic feature is the Sierra Nevada, which has a general northwest and southeast trend.

This relation of precipitation and topography is well shown by studying observations made along cross-sections of the Sierra Nevada laid out at right angles to the trend of the range. Two such sections are indicated on Fig. 1 as the Central Pacific and Mokelumne Sections. The relations of mean annual precipitation, altitude, topographic position, and profiles of ground surface are presented graphically for the two sections in Diagrams 1 to 6 of Plate II. The marked similarity in the curves for the two sections indicates that the quantity of precipitation at points in a transverse section of the range conforms to some general law. Elevation, obviously, is not the controlling factor, for above the 5 000-ft. level the precipitation decreases with increase in altitude. The slope of the ground surface appears to be the most important element involved, as is seen from Diagrams 2, 3, 5, and 6 of Plate II. The phenomenon results from the condensation of aqueous vapor due to adiabatic cooling of masses of moist air driven up the slope of a mountain range by the prevailing winds. The region of maximum precipitation is at the lower cloud limit on the windward slope of the range, and above this the latent heat liberated by condensation raises the temperature above the dew point, resulting in decreased precipitation. After crossing the summit of a high range, the descending mass of air contracts in volume, thereby raising the temperature rapidly above the dew point and resulting in marked decrease of precipitation.

The increase of precipitation with elevation was first observed by Mr. S. A. Hill,* in studying rainfall in the northwest Himalayas of

* "California Hydrography," by J. B. Lippincott, M. Am. Soc. C. E., Water Supply Paper No. 81, U. S. Geological Survey, p. 354.

India, and he developed for that region the empirical formula, $R = 1 + 1.92h - 0.40h^2 + 0.02h^3$, in which R represents the quantity of rain and h the relative height, in units of 1 000 ft., above an assumed plane which is itself 1 000 ft. above sea level. This equation, when platted, gives a curve very similar to that shown in Diagrams 1 and 4 of Plate II, the plane of maximum rainfall being 4 160 ft. above sea level. The equation does not apply to conditions on the leeward slope of a range, however, to judge by the discontinuity at the crest line shown on the Sierra Nevada curves. The straight-line relation between precipitation and elevation, which is often assumed in engineering computations, thus appears to have a very limited use, and to be at best a rough approximation.

The Los Angeles Aqueduct precipitation stations in Owens Valley lie in three groups, indicated on Fig. 1 and Plate I, as the Taboose, Oak, and Bairs Sections. The 2-year records for these stations were reduced to averages by comparison with the 26-year record at Independence. The platted curves for these sections (Plate II) are all similar in shape, and agree with the desert slope portion of the Central Pacific and Mokelumne curves. The highest point on each of the Owens Valley curves was obtained from the measured run-off of the canyons crossed by the section and a run-off factor chosen after careful study of precipitation and run-off data for Kings River, which drains the slope of the Sierra Nevada to the west. The precipitation at the mouth of the canyons was known from the rain gauge observations, and the average precipitation over each canyon from the run-off. Most of these canyon drainage areas are isosceles triangles in plan, the base being along the crest of the mountains. Also, judging by the Central Pacific and Mokelumne Sections, the precipitation increases uniformly from the base of the mountains on the desert side to the summit. Hence, the precipitation at the center of area of each drainage basin is equal to the average precipitation over the whole area, and the precipitation at the summit is obtainable by a simple proportion.

Preliminary to the establishment of isohyets or lines of equal annual precipitation for the Independence Basin, a broad study of precipitation was made for the whole Sierra Nevada range from Lake Tahoe to the Mojave Desert (Fig. 1). This was based on the California Water and Forest Association rainfall map of the State, pre-

PLATE II.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.

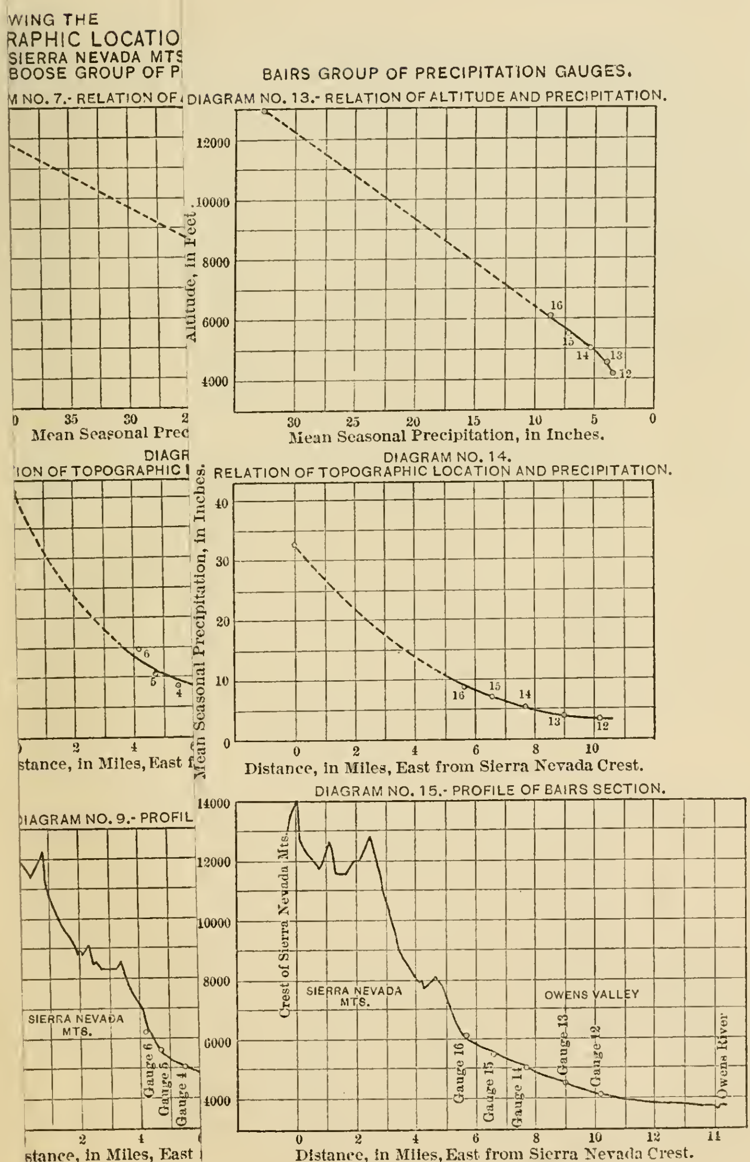
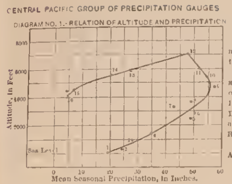


PLATE II.
TRANS. AM. SOC. CIV ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS

DIAGRAMS SHOWING THE
INFLUENCE OF ALTITUDE AND TOPOGRAPHIC LOCATION ON PRECIPITATION.
AS ILLUSTRATED BY THE SIERRA NEVADA MTS.

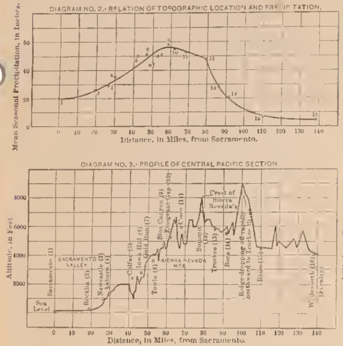


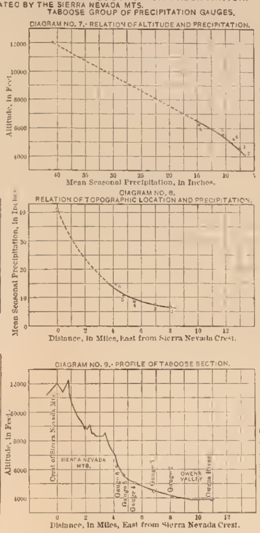
NOTES

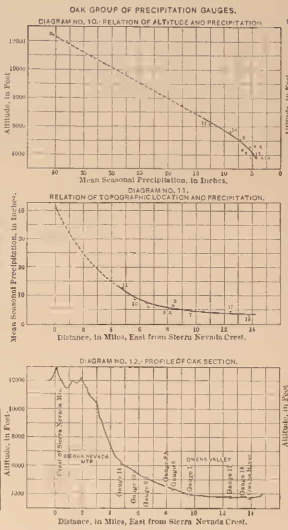
Observations on Central Pacific and Mokelumne Groups of gauges by U.S. Weather Bureau.

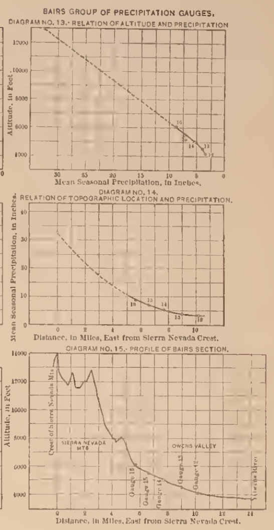
Observations on Taboose, Oak, and Bairs Groups of gauges by City of Los Angeles. (See Tables 16 and 17.) For location of gauges see Drainage Map of Sierra Nevada Mts, and Drainage Map of Independence Region.

The Season is from Sept. 1st to Aug. 31st.









pared in 1900, as revised between American and Kings Rivers by Edwin Duryea, Jr., M. Am. Soc. C. E., in 1908. With all available rainfall data to date, including the Los Angeles Aqueduct and several private records, the writer has made further revisions over the Southern Sierra and Owens Valley. The Water and Forest Association isohyets, as amended by Mr. Duryea, appear on Fig. 1 as solid lines, and revisions proposed by the writer are represented by dotted lines. Isohyets are shown with greater detail for the Independence Basin on Plate I.

Stream Flow.

Stream flow data essential to the determination of inflow and outflow for an underground reservoir, are the run-off from precipitation, the seepage from or into stream channels, and the flow of springs. Precipitation which finds its way into surface streams without absorption may, along some portion of the channel, percolate into porous gravels and join the subterranean supply. On the other hand, water may escape from the underground reservoir by seepage into stream channels where the general water plane is at a higher elevation than mean water level in the stream. Escape may also occur from springs.

The problem in the Independence Basin was, first, to classify the surface as to run-off characteristics and determine the run-off from each subdivision; second, to ascertain seepage losses from the seventeen tributary mountain streams between the canyon mouths and the valley floor; third, to determine the flow of springs which represent water escaping from the basin; and fourth, to ascertain whether Owens River made or lost water in passing through the basin.

Run-off.—It was early observed that the run-off characteristics of the four areas into which the region was classified for study (Table 1) were similar.

The clay soils of the valley floor occasionally yield a small run-off during and following winter precipitations of 1 in. or more in 24 hours, or warm rain falling on old snow. This water gathers and passes off into Owens River within a few hours by way of four waste channels. A study of the available data shows that the average total run-off from precipitation on the valley floor is about 2 sec-ft. of continuous flow.

The outwash slopes yield no appreciable surface run-off, on account of the porous gravel formation and the great depth to ground-

water. This fact has been established by repeated observations during and after rainstorms and thaws, and is confirmed by the noticeable absence of recent drainage channels or washes, except those of streams which derive their water from high mountain drainage areas.

The intermediate mountain slopes yield a small run-off during May and June, when the temperature at that level is sufficient to melt the accumulated winter snow, but the small streams do not advance far over the outwash slopes before they are entirely absorbed. If the precipitation of the preceding winter is below normal, the snow melts before the hot weather comes, and is absorbed at once. Springs are common along the lower borders of these slopes, the source being the melted snow absorbed by the porous material above and brought to the surface where it comes into contact with impervious formations. In only a few places does such water find its way into living streams.

The high mountain drainage areas have an abundant run-off, and perennial streams flow from all but one of them. The source of this water is precipitation, in the form of snow and rain, which falls within the drainage areas, and to a small extent snow dust carried over the summits by the prevailing west and northwest winds of winter and spring. For all practical purposes, the average discharge at the mouth of the canyon represents the average precipitation within the drainage area minus losses by evaporation from exposed snow surfaces. The underflow from these areas is negligible.

Stream discharge from the canyons is at a minimum from September to April. The flow during these months is remarkably uniform, and is entirely uninfluenced by the current storms, though from 70 to 80% of the annual precipitation occurs between November 1st and March 31st. The low-water flow is derived from springs and from the slow melting of the snow layer exposed to the earth's latent heat. Streams are usually frozen over by November, and as late as April they flow nearly to the mouths of the canyons in tunnels under the snow. Between April 1st and 20th air temperatures increase sufficiently to melt the snow at the lower elevations, and the streams begin to rise. There is an increase in air temperatures and stream flow from this date until the maximum flood crest is reached, some time between June 15th and July 15th, depending on the quantity of snow to be melted. Stream flow then decreases until some time in September,

after which low water prevails. About 70% of the annual run-off of the streams occurs during May, June, July, and August.

Percolation from Stream Channels.—The United States Geological Survey gauging stations on streams draining the high mountain areas are at the lower edges of the outwash slopes, just above the division boxes which apportion the water for use on the ranches of the valley floor. After leaving its canyon each stream traverses several miles of channel before reaching the gauging station, and preliminary observations in June, 1908, showed that considerable water (in some streams 50%) disappeared between the two points. It was necessary, therefore, either to establish regular gauging stations at the canyon mouths and depend on records for short periods, or to devise some means of computing the run-off from the high mountain areas from the existing Government records, which extended over 6 years. The latter method was chosen, and the results have proved very satisfactory.

The loss from these stream channels occurs as percolation into the porous alluvial material, direct evaporation from water surface, and transpiration from vegetation growing along the stream borders. Evaporation and transpiration losses were too small to be detected in current-meter work. As the expense of installing and maintaining weirs was prohibitive, the problem resolved itself into a study of percolation from stream channels.

There are three factors to be considered in a study of the subject: the rate of percolation, the area through which percolation occurs (the wetted perimeter), and the period of time during which a given unit of water is exposed (velocity of flow). The rate of percolation depends on (1) the character of the channel lining and the medium surrounding the channel, as regards size of pores and porosity; (2) the pressure gradient, depending on the difference in level of the surface of the water in the channel and the ground-water surface; and (3) the temperature of the water.

The effect of an increase in the wetted perimeter, other conditions being the same, is obviously to increase the percolation, but such change is accompanied by a proportionally larger increase in the velocity of flow, which reduces the time of exposure of a given volume of water. The net result, considering the total flow, is, therefore, a proportionally smaller percolation, although this effect may be counter-

acted to a certain extent by the scouring of a non-porous channel lining due to the increased carrying power of the stream. The whole matter is affected by so many indeterminate conditions that a general mathematical analysis is impossible, but, with these ideas in view, a study was made of each channel within the ordinary range of temperature and discharge.

The field work consisted of making comparative current-meter measurements at upper and lower stations on each creek, giving proper allowance of time for the passage of water between the two points. The measurements were made at intervals of from 6 weeks to 2 months, and extended over the period from June 15th, 1908, to September 15th, 1909, including the high-water periods of wet and dry seasons. Gauging sections were prepared at the mouth of the canyon on each creek. Estimates of the time required for the passage of water between stations were based on actual trial with aniline dye. Very little fluctuation in discharge was observed in any of the creeks between 8 A. M. and 5 P. M., even in the high-water period.

The temperature of the water as it issues from the canyons varies from 35° to 42° Fahr., in winter, and from 48° to 53° Fahr., in summer. In winter the temperature does not increase much as the water travels toward the valley. After leaving the protecting cover of the snow in the canyons during December and January the water actually becomes colder, ice prevailing for several weeks. In summer there is an average increase of 10° between the stations at the mouth of the canyon and in the valley.

Several methods were attempted for generalizing the results, but the most satisfactory was a graphical one, in which losses were platted as abscissas and stream discharges as ordinates with rectangular coordinates (Plate III).

It was found that for each channel a straight line expressed the relation of these two quantities from April to October, inclusive. During the remaining 5 months, the relation is not clear, but the total loss is then so small that it can be obtained by inspection without affecting the accuracy of the computed discharge at the mouth of the canyon. Total losses are platted on the basis of discharge, both at lower and upper stations, so that, in correcting the Government records to obtain the true yield from high mountain drainage areas, the quantity desired can be obtained at once by entering on the X-axis

N THE VICINITY OF INDEPENDENCE

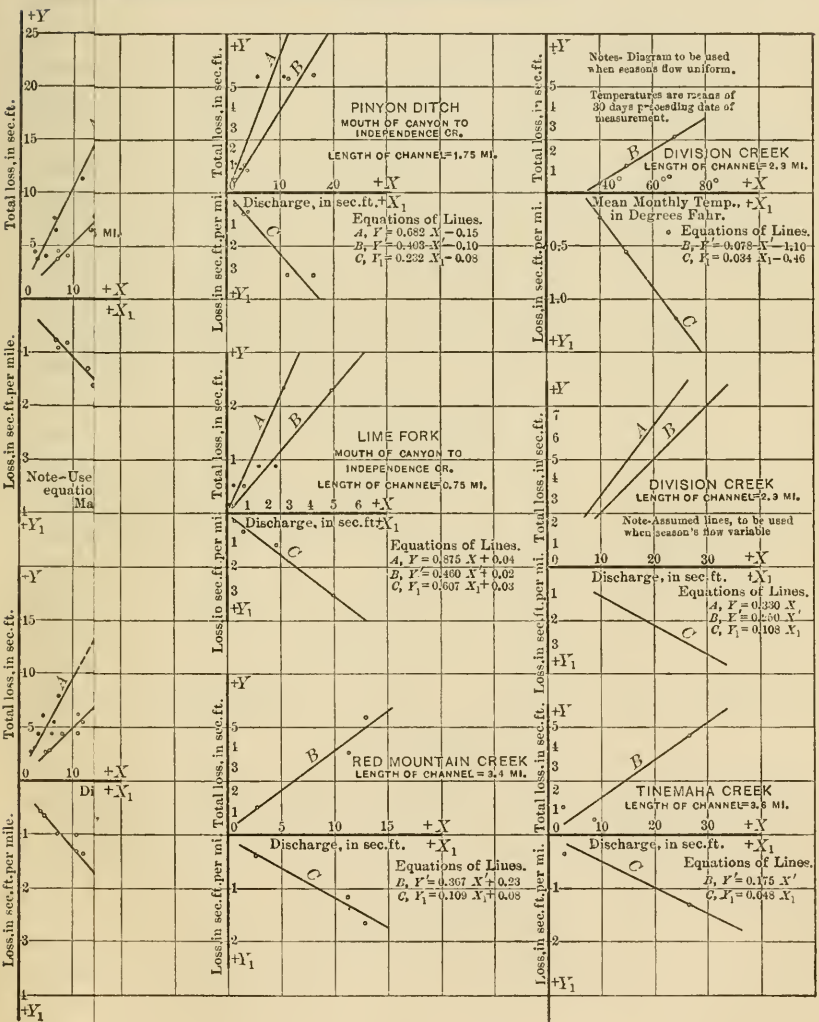
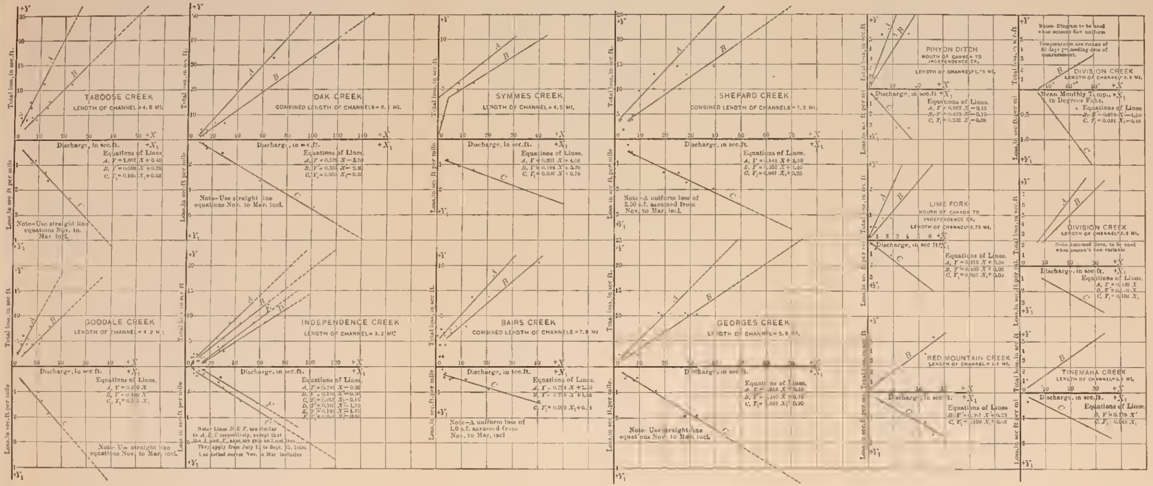


PLATE III.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.

SEEPAGE LOSS DIAGRAMS FOR OUTWASH SLOPE CHANNELS OF STREAMS DRAINING HIGH MOUNTAIN AREAS IN THE VICINITY OF INDEPENDENCE



the discharge at the lower or Government station. It is also possible at the same time to read the loss, in second-feet to the mile, from the straight line below the X-axis.

The diagrams on Plate III were prepared for the purpose of computing (1) seepage losses above the U. S. Geological Survey gauging stations, and (2) the actual yield of high mountain drainage areas. In obtaining the field data, discharge measurements were made with small Price current meters during the period, June to August, 1909, inclusive, covering a season of small run-off and one of large run-off. The accuracy is up to the standard for a stream of this type. Measurements of medium and high stages were difficult, on account of the rough sections and very high velocities. The upper gauging station is at the mouth of the canyon, or below impervious dikes forcing seepage water to the surface. The average elevation is 6 000 ft. The lower station is that used by the U. S. Geological Survey (unless otherwise noted), which is above the diversion and has an average elevation of 4 100 ft. Below the latter there is ½ mile or more of channel suffering a large seepage loss which is not included. The length of the channel was obtained by scaling from the Mt. Whitney Quadrangle, and, for Taboose, Red Mountain, and Tinemaha Creeks, from a triangulation survey. Elevations were obtained in a similar manner. In using the diagrams, the straight-line relation applies from April to October, inclusive, during which time temperature and discharge vary similarly. The dotted portions are not supported by field data, and are to be used with judgment. From November to March, inclusive, temperature is the only effective variable, and arbitrary values for loss have been selected. Line "A" expresses the relation of total loss to discharge at the U. S. Geological Survey Station; Line "B" expresses the same relation at the mouth of the canyon; and Line "C" expresses the loss per mile to discharge at the mouth of the canyon. The diagrams are arranged so that all the four values involved may be obtained by entering any one of them.

There are some interesting conclusions to be drawn from these diagrams. In general, the quantity of water percolating from the channels studied varies with the time of year and with different channel conditions. Variation with the time of year is due to the combined effects of temperature, area of wetted perimeter, and velocity of flow. These work more or less in harmony during April to October, inclusive,

and produce the straight-line relation of total loss and discharge. From November to March, inclusive, canyon discharges remain practically constant, showing that variations are largely controlled by temperature. Discharges are then so small, however, that errors of measurement are appreciable, and losses by evaporation have greater weight, so that the true relation of loss and temperature does not appear. A possible relation between total loss and temperature is suggested by the results on Division Creek, where the discharge at the mouth of the canyon was practically uniform during the period of study. Using as ordinates the mean air temperature at Independence for the 30 days preceding each date of measurement, we obtain a straight line which crosses the X-axis at about 35 degrees. A line supported by additional data might cross nearer 32°, the temperature at which percolation becomes physically impossible.

The character of the surrounding medium was the only channel condition which noticeably affected percolation. The loss from a channel crossing fissured lava, even where the lava was covered by a thin sheet of alluvium, was 30% greater than that in coarse alluvium. The streams studied do not overflow their channels, so that the effect of varying channel slopes and wetted perimeter could not be studied.

The run-off from each mountain canyon was computed from U. S. Geological Survey monthly mean discharge records, by use of the diagrams. The results are summarized in Tables 4 and 5. The missing seasons were estimated from the unbroken records of neighboring streams after a detailed study of yield per square mile and annual departure from normal for each stream. The long-term mean discharge was obtained by comparison with the Kings River record, which covered 21 years. This stream was chosen because its drainage area adjoined most of the Owens Valley streams and because conditions affecting run-off were more nearly similar than on any other stream. The results indicate that the total annual mountain run-off during the period of record was 153 annual sec-ft. and the normal 130 annual sec-ft. This total does not include Red Mountain and Tinemaha Creeks, which pass out of the basin after crossing a portion of the outwash slope. The normal run-off per square mile for streams north of the Kings-Kern divide with 60% or more of area above 10 000 ft., is 1.75 sec-ft., and, for streams similarly situated, with less than 60% above 10 000 ft., 1.18. For streams south of the Kings-Kern divide,

TABLE 4.—SEASONAL DISCHARGE, IN SECOND-FEET, AT UNITED STATES GEOLOGICAL SURVEY STATIONS, OF CREEKS TRIBUTARY TO INDEPENDENCE REGION.

(Figures in parentheses are estimated.)

Creek.	Year Beginning September 1st.						Observed 5-year mean.	Computed 21-year mean.
	1904.	1905.	1906.	1907.	1908.	1909.		
Taboose	(5.7)	11.4	10.3	4.7	8.6	5.9	8.2	6.5
Goodale	(3.9)	5.4	6.6	3.8	6.4	5.3	5.5	4.3
Dry Canyon	0	0	0	0.0	0	0	0	0
Division	(3.9)	7.2	10.9	7.6	9.7	9.9	9.1	7.2
Sawmill	....	5.4	(7.6)	(5.0)	7.3	7.2	6.5	5.1
Thibaut	(0.5)	(1.0)	(1.0)	0.8	0.9	0.2	0.6	0.5
Oak	(13.0)	31.8	23.9	15.8	30.8	18.4	24.1	19.0
Little Pine, Pinyon	(10.7)	28.5	22.5	11.8	25.8	17.2	21.2	16.7
Symmes	....	(2.8)	3.1	0.8	6.3	1.1	2.8	2.2
Shepard	....	23.1	11.0	7.2	12.9	7.7	12.5	9.8
Bairs	....	8.0	4.8	2.0	6.1	2.4	4.7	3.7
George	....	18.6	10.9	6.5	13.0	6.8	11.2	8.8
Hogback	(0)	(1.0)	(0.5)	(0)	(0.5)	0	0.4	0.3
	....	144.2	113.1	66.0	128.3	82.1	106.7	84.0
Percentage of totals at mouth of canyon....	....	68	63	61	66	63	65	65

TABLE 5.—SEASONAL DISCHARGE, IN SECOND-FEET, AT MOUTH OF CANYON, OF CREEKS TRIBUTARY TO INDEPENDENCE REGION.

(Figures in parentheses are estimated.)

Creek.	Year Beginning September 1st.						Observed 6-year mean.	Computed 21-year mean.
	1904.	1905.	1906.	1907.	1908.	1909.		
Taboose	11.9	19.2	20.4	9.8	16.0	12.4	15.0	12.7
Goodale	7.6	9.9	12.3	7.2	11.2	10.2	9.8	8.3
Dry Canyon	(3.9)	(5.1)	(6.3)	(3.7)	(5.7)	(5.2)	5.0	4.2
Division	(4.4)	6.9	11.2	6.9	8.7	9.5	7.9	6.7
Sawmill	(4.0)	6.5	9.1	5.5	7.3	7.2	6.6	5.6
Thibaut	(1.9)	(3.1)	(4.4)	(2.7)	(3.5)	(3.4)	3.2	2.7
Oak	16.7	43.2	33.8	21.2	42.6	25.0	30.4	25.8
Little Pine	10.7	24.6	20.5	12.0	24.3	16.7	18.1	15.3
Pinyon	(3.6)	(8.9)	(6.6)	(4.2)	9.2	3.5	6.0	4.8
Symmes	(3.5)	(8.8)	7.0	3.7	10.2	4.9	6.2	5.3
Shepard	(11.1)	31.4	18.9	13.5	2.09	14.1	18.3	15.5
Bairs	(4.3)	11.8	7.7	4.2	9.4	4.8	7.0	5.9
George	(8.2)	23.8	16.5	9.8	18.7	10.3	14.6	12.4
Hogback	(2.8)	(7.8)	(5.7)	(4.2)	(6.8)	(3.7)	5.2	4.4
	94.6	211.0	180.4	108.6	194.5	130.9	153.3	129.6
Percentage reaching U. S. G. S. Stations.	....	68	63	61	66	63	65	65

the normal run-off is 1.36 and 0.86 sec-ft., respectively. It is also of interest to note that only 65% of this run-off reaches the Government gauging stations.

Springs.—The occurrence of springs in the basin is due to the reappearance of water which originally fell within its boundaries as precipitation and was absorbed. There are, in general, three types of springs which give rise to surface streams: those which derive their supply from precipitation on the intermediate mountain slopes, and appear at the base of these slopes; those which derive their supply from precipitation and stream percolation, and appear along the upper edge of the grass land; those which derive their supply from precipitation on lava flows, and appear at the lower borders of the flows.

The springs of the first type are not deep seated; they represent the drainage from the superficial deposits lying on the triangular mountain slopes between canyons. The temperature of their water is about 47° or 48° Fahr., and the flow in many of them increases in early summer and decreases during late summer and autumn. The water from most of these springs sinks into the porous gravels of the outwash slope, and joins the main body of ground-water in the basins.

The line of springs along the upper edge of the grass land represents the intersection of the natural surface of the ground and the surface of the ground-water. The water has penetrated rather deeply into the gravel fill, and issues with a temperature of about 62° Fahr., which is 5° higher than the mean annual temperature at Independence and 1° lower than that of water flowing from Artesian wells in the same location. The flow of these springs is variable, being least in late summer and greatest in early spring, with regular fluctuation between these dates, evidently depending on ground-water stages within the grass area. Only during the winter months is the discharge sufficient to be the source of surface streams which flow any considerable distance, and even then there are only a few of such streams which reach Owens River. Most of the yield of these springs is lost by evaporation and transpiration. The winter discharge of individual springs varies from 0.5 sec-ft. down to a quantity which is only enough to fill small pools of standing water, from which the evaporation equals the yield. The total winter discharge from all these springs is about 4 sec-ft.

The springs issuing from the lava formations are unique in having uniform discharges throughout the year and a temperature of 57° Fahr. The water is probably derived from precipitation on the lava surface, absorbed by the porous rock, and, by reason of the peculiar formation, gathered and delivered at the lower margin of the flow. The largest of these is Blackrock Springs (Plate I), 9 miles north of Independence. It has a discharge of 23 sec-ft., which flows out across the valley floor in two sloughs, each emptying into a series of shallow lakes. From November to March, inclusive, an average flow of about 7 sec-ft. reaches Owens River, but during the remainder of the year all the water is lost by seepage, evaporation, and transpiration. Hines Spring is 3 miles north of this spring, and has a continuous yield of about 4 sec-ft. Approximately, 1 sec-ft. finds its way into Owens River during the winter, but is lost during the remainder of the year. Campbell Spring is east of Owens River, 1 mile north of Aberdeen. It has a yield of about 0.5 sec-ft., and discharges directly into the river. Upper and Lower Seeley Springs are just above and just below Charlies Butte, and discharge directly into Owens River. The upper spring has a flow of 9.5 sec-ft., which is included in measurements of Owens River at the Butte. The lower one has a flow of 1.5 sec-ft.

Owens River.—Owens River flows lengthwise of the Independence Basin for 29 miles, although the actual length of its channel is possibly 20% greater, owing to its sinuosity. It is the drainage outlet for the waste surface water of the region, including the run-off from the valley floor, the yield of springs, and a small portion of the run-off from high mountain drainage areas. In order to account for all escaping surface waters, and determine the condition of the river channel with regard to seepage, observations of river discharge were made daily near the north and south boundaries of the region, and measurements of discharge into and diversion from the river channel were made between these two points. Complete data are available for 1909 and 1910. Analysis of these data shows that seepage losses occur during high-water, and seepage gains during low-water stages. The net result is a loss between Charlies Butte and Whitney Bridge, which can be accounted for by channel evaporation. The water plane of the valley on each side of the river lies between high- and low-water levels in the river. Hence, seepage gain and loss are the result of local ab-

sorption and drainage along the river channel, and have no relation to the general ground-water situation of the basin.

Evaporation and Transpiration.

Evaporation from Water Surfaces.—Measurements of evaporation from free water surfaces were made under three conditions: from a pan floating in a body of water, from a pan placed in the soil, and from a deep tank placed in the soil. The first and second were designed to furnish data regarding evaporation from reservoir surfaces and from areas of shallow flood water, respectively. The third was desired for purposes of comparison with records of evaporation from soil. The pans, which were of the pattern used by the U. S. Reclamation Service, were 3 ft. square and 10 in. deep, and were of galvanized sheet-iron. Observations were made by replacing the quantity evaporated with a cup having a capacity equal to a depth of 0.01 in. in the pan. The initial height of the water surface was such that a pin, projecting from the center of the pan and remaining at a fixed height, 2 in. below the rim, was just submerged. The deep tank was circular, 3½ ft. in diameter and 4 ft. deep, and observations were made in a stilling well with a hook-gauge and vernier scale reading to 0.01 in. The records were all kept near Independence, and observations were made every second day in summer and every fourth day in winter.

The record for the pan in water (Table 6) is available from August 4th, 1908, to June 1st, 1911. The pan, Fig. 3, at first, was in Blackrock Slough, but was moved to its final location, in Owens River at Citrus Bridge, on May 7th, 1909. The pan was supported by a timber float, which protected it from splashing water. The depth of water beneath the pan varied from 1 to 5 ft., depending on the river stage. The river water had a moderate velocity, and varied in temperature from about 75° Fahr., in summer, to about 40° Fahr., in winter. The river banks averaged 4 ft. high above the water surface, and the pan was about 30 ft. from them. Rain gauge No. 18 was 100 ft. away, on the river bank, and was observed in connection with the evaporation record.

The record for the pan in soil is broken. It extends from August 1st, 1909, to November 30th, 1909, and from March 14th, 1910, to June 1st, 1911. The pan, Fig. 4, was in the valley floor at the soil evaporation experiment station, about 3 miles east of Independence.

It was set in a shallow excavation with soil banked up to about half the depth of the pan. Water temperatures range from 95° Fahr., in summer, to 32° Fahr., in winter. The surface temperature was about 1° warmer than that for the mixed contents of the pan. Table 7 summarizes the results by months for this pan, and, by comparing it month by month with the evaporation from the pan in water, an average excess of about 33% is observed. This is probably due to the higher temperature of the water in the pan in soil during the hours of sunlight.

TABLE 6.—DEPTH OF EVAPORATION, IN INCHES, FROM WATER SURFACE NEAR INDEPENDENCE (PAN IN WATER).

Month.	1908.		1909.		1910.		1911.		Average percentage of annual evaporation.
	Total.	Rate per 24 hours.	Total.	Rate per 24 hours.	Total.	Rate per 24 hours.	Total.	Rate per 24 hours.	
January	....	....	1.60	0.052	1.75	0.056	1.65	0.053	2
February	....	....	2.40	0.086	2.50	0.089	2.35	0.084	4
March	....	....	4.70	0.152	5.15	0.166	3.70	0.119	7
April	....	....	7.30	0.243	7.05	0.235	6.25	0.208	11
May	....	....	9.60	0.310	8.29	0.267	8.01	0.258	13
June	....	....	10.10	0.337	9.90	0.330	....	....	15
July	....	....	10.40	0.335	8.50	0.274	....	....	14
August	* 4.90	0.222	8.00	0.258	8.20	0.264	....	....	12
September	5.30	0.176	6.60	0.220	6.30	0.210	....	....	10
October	3.50	0.113	3.90	0.126	4.20	0.135	....	....	6
November	2.50	0.083	2.60	0.087	2.36	0.079	....	....	4
December	1.50	0.048	(1.85)	0.060	1.24	0.040	....	....	2
	....	....	69.05	0.189	65.44	0.179	....	....	100

* August 10th to 31st, inclusive.

The deep-tank record extends unbroken from April 16th, 1909, to Dec. 31st, 1911. The tank, Fig. 6, was at the soil evaporation experiment station, and was set in the soil with the upper rim flush with the surface. The water surface was not allowed to fall more than 4 in. below the rim. The temperature of the surface water varied from 80° Fahr., in the heat of summer to freezing in winter. Except during freezing weather, the average temperature of the contents of the tank was 5° less than that of the surface layer. The presence of the surrounding soil makes the range in temperature less than that for the shallow pan. The record, which is presented in Table 8, indicates an annual depth of evaporation practically equal to that from the pan in water at Citrus Bridge. The monthly distribution is more uniform,

TABLE 7.—DEPTH OF EVAPORATION, IN INCHES, FROM WATER SURFACE NEAR INDEPENDENCE (PAN IN SOIL).

Month.	1909.			1910.			1911.		
	Total.	Rate per 24 hours.	Percentage of evaporation from pan in water.	Total.	Rate per 24 hours.	Percentage of evaporation from pan in water.	Total.	Rate per 24 hours.	Percentage of evaporation from pan in water.
January	....	....	....	....	....	....	2.25	0.073	138
February	....	....	....	....	....	....	2.25	0.080	95
March	....	....	....	* 4.25	0.236	....	4.80	0.155	130
April	....	....	....	9.50	0.316	135	8.12	0.271	130
May	....	....	....	10.61	0.342	128	10.25	0.330	128
June	....	....	....	11.95	0.398	121	....	....	....
July	....	....	....	12.55	0.405	148	....	....	....
August	10.70	0.345	134	11.80	0.381	144	....	....	....
September	8.50	0.283	129	8.80	0.293	140	....	....	....
October	5.80	0.187	149	5.60	0.180	133	....	....	....
November	3.80	0.127	146	2.85	0.095	121	....	....	....
December	....	....	....	1.60	0.052	129	....	....	....
	....	....	....	....	....	133	....	....	....

* March 14th to 31st, inclusive.

TABLE 8.—DEPTH OF EVAPORATION FROM WATER SURFACE NEAR INDEPENDENCE.

DEEP TANK IN SOIL.

Month.	1909.			1910.			1911.			Percentage of annual evaporation during each month.
	Total, in inches.	Rate, in inches per 24 hours.	Percentage of evaporation from pan in water.	Total, in inches.	Rate, in inches per 24 hours.	Percentage of evaporation from pan in water.	Total, in inches.	Rate, in inches per 24 hours.	Percentage of evaporation from pan in water.	
Jan	....	....	....	2.00	0.064	114	2.30	0.074	139	3
Feb	....	....	....	2.90	0.104	116	2.55	0.091	108	4
Mar	....	....	....	5.60	0.180	109	3.95	0.127	107	7
Apr	2.90*	0.193	....	7.40	0.246	105	6.80	0.226	84	10
May	7.50	0.242	78	7.71	0.248	93	7.90	0.254	77	12
June	7.80	0.260	77	8.60	0.287	87	6.65	0.222	....	11
July	7.90	0.254	76	8.30	0 268	98	8.60	0.277	....	12
Aug	8.20	0.264	102	8.80	0.284	107	9.65	0.311	....	14
Sept	7.20	0.240	109	7.30	0.243	116	7.16	0.239	....	11
Oct	5.00	0.161	128	5.15	0.166	123	4.90	0.158	....	7
Nov	3.30	0.110	127	3.10	0.103	131	3.00	0.100	....	5
Dec	(2.20)	0.071	119	2.15	0.069	173	(2.50)	0.081	....	4
Totals	......	......	......	69.01	0.188	106	65.96	0.180	....	100

* For period, April 16th to 30th, inclusive.

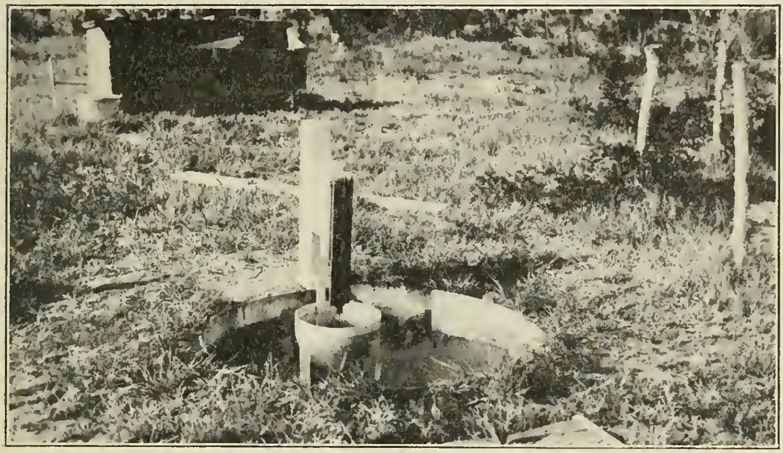


FIG. 6.—DEEP-WATER EVAPORATION TANK.

FIG. 7.—SOIL TANK NO. 3 IN OPERATION.

there being 70% of the total during the 6 summer months and a difference of 27 in. between summer and winter evaporation. The effect on evaporation of the modified temperature extremes of the soil is well shown by comparison with the record for the pan in water (Table 6). The temperature conditions for the deep tank agree closely with those of the surrounding soil.

Evaporation from Ground Surface.—Water in the surface layers of the ground is subject to evaporation, either directly from the soil or through vegetation by the process of transpiration. It is available for evaporation in Owens Valley under two conditions: temporarily, following a rainstorm or sudden thaw, and permanently, within areas where the average depth to ground-water does not exceed 8 ft. The total evaporation under the first condition is relatively unimportant, because of the infrequency of storms and the small quantity of precipitation, and no attempt was made to measure it. Under the second condition, however, evaporation losses are large, for, not only is soil capillarity able to draw gravity water to the surface, but roots of vegetation, such as wild grass, penetrate the soil to ground-water and become the channels by which a large quantity of moisture is conveyed into the atmosphere. Evaporation from bare soil combined with transpiration is, in fact, the most important element entering into computations relating to ground-water for this region. So few data are available on the subject that extended observations were undertaken.

Owens Valley is an ideal location for carrying on such experiments. In the first place, the source of water available for evaporation may be kept under the complete control of the observer as regards the quantity and rate of supply. Storms are rare, and the total precipitation is small, so that little uncertainty exists from this cause regarding the quantity of percolation from precipitation on the surface of a body of isolated soil. Second, the method by which the surface soils of the valley floor are kept moist can be reproduced artificially on a small scale with only a slight departure from natural conditions. The source of supply for soil moisture is a permanent ground-water surface from which water is drawn by capillary forces. This ground-water is replenished by percolation from the precipitation and surface water of the intermediate mountain and outwash slopes, which seeps laterally toward the valley floor and lies beneath it under hydrostatic pressure sufficient to maintain a permanent ground-water surface.

Similar pressure can be reproduced in the bottom layer of an isolated body of soil, and capillary forces can be depended on to raise moisture to the surface. Finally, the large annual depth of evaporation makes possible a more accurate determination of its quantity than in a less arid region. Experiments carried on under these conditions have been very satisfactory.

The rate of evaporation from soil depends on the temperature of the air and soil, the quantity of moisture already in the immediately surrounding atmosphere, the quantity of moisture in the surface layers of the soil, and the character of the vegetation and other soil covering. The first two of these factors have the same effect on soil evaporation as on that from a free water surface—higher air and soil temperatures result in increased evaporation, as does also dryer atmosphere or increased movement of wind. The third factor is directly proportional to the rate of evaporation, because the loss of moisture occurs from soil grains at or very near the surface. The quantity of moisture in the soil available for evaporation thus depends on the character of the soil, as regards capillarity and depth to the ground-water surface. For example, in a coarse, sandy soil, "gravity water" will be drawn to the surface through the capillary spaces from depths not exceeding 4 ft., and, in a fine sandy or clayey soil, water will be drawn from depths as great as 8 ft. The last factor, the extent and character of vegetation, affects the evaporation rate both through the activity of transpiration and the effect on capillarity. Plant roots are continually absorbing water from the soil; this water passes off into the atmosphere through the leaves, and the evaporation losses from soil are greatly increased thereby. The roots of native salt grass will penetrate to a depth of 8 ft. in search of water. A further effect of the growth of vegetation is to increase the vertical capillary flow of moisture through soil by way of the many tubes filled with the rotted fiber of dead roots. These tubes are the result of years of growth, and penetrate the soil in all directions above the ground-water surface.

The purpose of the experiments was to obtain data sufficiently complete to compute the total volume of water annually lost by evaporation and transpiration from the valley floor. This involved making observations under the various local conditions which affect soil evaporation. The plan was to reproduce natural conditions in isolated bodies of typical soil and determine the evaporation therefrom for

varying climatic conditions, depths to ground-water, soils, and vegetation.

The experimental equipment consists of two galvanized-iron tanks, $6\frac{1}{2}$ ft. in depth, connected at the bottom by an 18-ft. length of galvanized pipe. (See Fig. 8.) The smaller tank is 2 ft. $4\frac{3}{16}$ in. in diameter, and has a tight-fitting cover. The larger tank is 7 ft. $5\frac{1}{4}$ in. in diameter, and has a system of branching perforated pipes at the bottom connected with the pipe from the smaller tank. The two tanks and all connections are water-tight, and water poured into the smaller or reservoir tank passes into the larger or soil tank and escapes through the perforations. These two tanks were placed in excavations of proper size to receive them, the soil tank was filled with the excavated soil, and the reservoir tank was filled with water. A 6-in. layer of screened gravel, too coarse to enter the $\frac{1}{16}$-in. perforations, was laid in the bottom of the soil tank in order to insure an uninterrupted and well-distributed feeding of water from the reservoir tank into the superimposed soil. As soon as the material became saturated and capillary action was established to the surface, the water level in the soil was brought to the desired depth and kept there by supplying water to the reservoir tank in measured quantities. Volumetric measurements of water poured into or withdrawn from the reservoir tanks were made with an ordinary gallon measure. Accumulation or depletion of the supply in the reservoir tank was determined volumetrically by measuring the depth of water with a steel tape. The volume passing out of the reservoir tank during a given period represents the total evaporation from the soil tank during that period.

The position of the ground-water surface in the soil tank was determined by measuring its depth below the ground surface in 2-in. augur holes bored in the soil to a proper depth. Measurements were made from a fixed point with a steel tape weighted at the end and chalked before each observation. Three holes were placed in each tank, half way between the center and rim, on radii 120° apart. The holes were not bored deep enough to reach the bottom layer of coarse gravel, and the water level in them represented the ground-water surface in the surrounding soil. An average of the observations made at a given time was assumed to represent the general depth to ground-water for the tank at that time. The tendency of the sides of the holes to cave in and the bottom to fill with sand was controlled by casing

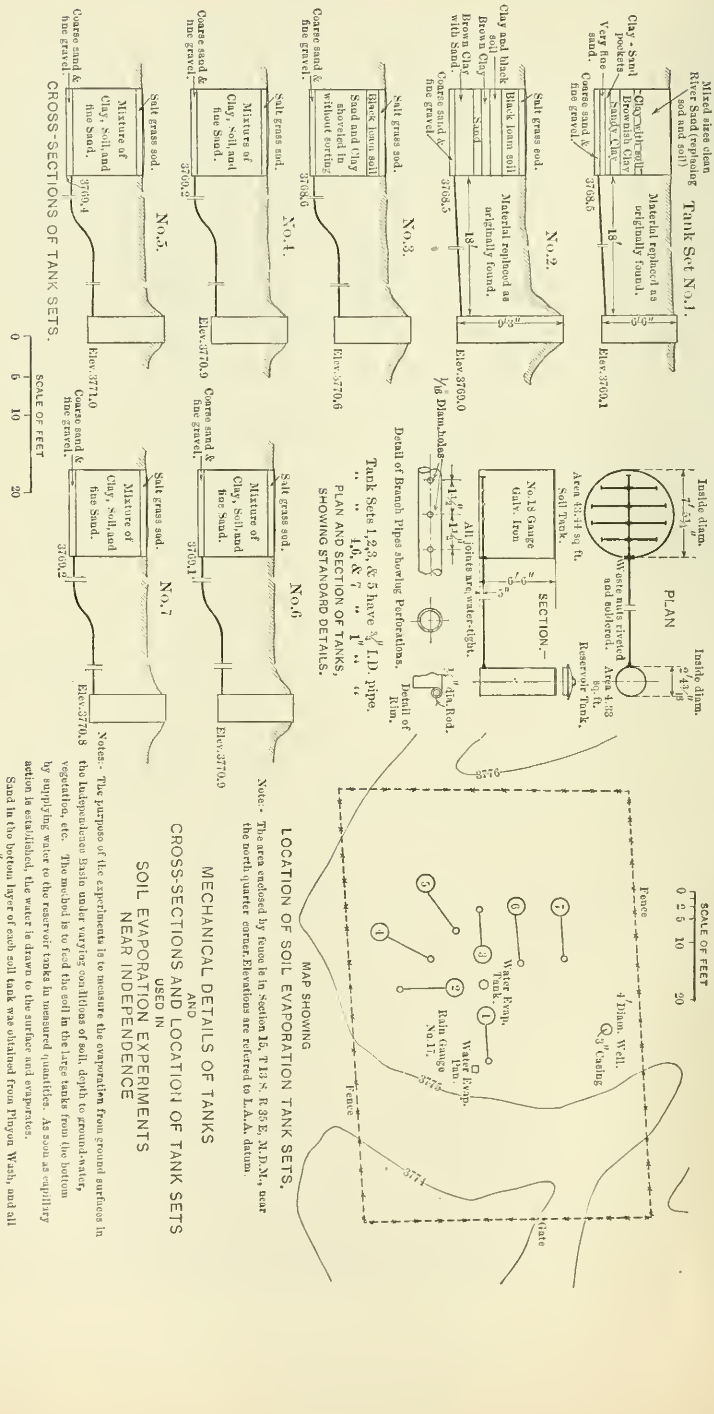

Tank Set No.1.
Mixed sizes clean River Sand (replacing sod and soil)
Clay - Sand pockets
Very fine sand.
Coarse sand & fine gravel.
Clay with soil
Brownish Clay
Sandy Clay
Material replaced as originally found.
3768.5
18′
6′6″
Elev.3769.1
No.2.
Salt grass sod.
Clay and black soil
Brown Clay
Brown Clay with Sand.
Coarse sand & fine gravel
Black loam soil
Sand
Material replaced as originally found.
3768.5
18′
9′3″
Elev.3769.0
No.3.
Salt grass sod.
Black loam soil
Sand and Clay shoveled in without sorting
Coarse sand & fine gravel.
3768.6
Elev.3770.6
No.4.
Salt grass sod.
Mixture of Clay, Soil, and fine Sand.
Coarse sand & fine gravel.
3769.2
Elev.3770.9
No.5.
Salt grass sod.
Mixture of Clay, Soil, and fine Sand.
Coarse sand & fine gravel.
3769.4
Elev.3771.0
CROSS-SECTIONS OF TANK SETS.
SCALE OF FEET
0 5 10 20
PLAN
Inside diam. 7′5¼″
Area 43.44 sq. ft.
Soil Tank.
Waste nuts riveted and soldered.
Inside diam. 2′4 13/16″
Area 4.33 sq. ft.
Reservoir Tank.
SECTION.—
No. 18 Gauge Galv. Iron
6′6″
5″
All joints are water-tight.
1/2″ dia. Rod.
Detail of Rim.
1/16″ Diam. holes
1½″ 1½″
Detail of Branch Pipes showing Perforations.
Tank Sets 1,2,3, & 5 have 3/4″ I.D. pipe.
" " 4,6, & 7 " 1" " "
PLAN AND SECTION OF TANKS, SHOWING STANDARD DETAILS.
No.6
Salt grass sod.
Mixture of Clay, Soil, and fine Sand.
Coarse sand & fine gravel.
3769.1
Elev.3770.9
No.7
Salt grass sod.
Mixture of Clay, Soil, and fine Sand.
Coarse sand & fine gravel.
3769.2
Elev.3770.8
SCALE OF FEET
0 2 5 10 20
Fence
4′ Diam. Well. Q 3″ Casing
Water Evap. Tank.
Rain Gauge No.17.
Water Evap. Pan.
3776
3775
3774
Gate
MAP SHOWING
LOCATION OF SOIL EVAPORATION TANK SETS.
Note:- The area enclosed by fence is in Section 15, T 13 S, R 35 E, M.D.M., near the north quarter corner. Elevations are referred to L.A.A. datum.
MECHANICAL DETAILS OF TANKS
AND
CROSS-SECTIONS AND LOCATION OF TANK SETS
USED IN
SOIL EVAPORATION EXPERIMENTS
NEAR INDEPENDENCE
Notes:- The purpose of the experiments is to measure the evaporation from ground surfaces in the Independence Basin under varying conditions of soil, depth to ground-water, vegetation, etc. The method is to feed the soil in the large tanks from the bottom by supplying water to the reservoir tanks in measured quantities. As soon as capillary action is established, the water is drawn to the surface and evaporates.
Sand in the bottom layer of each soil tank was obtained from Pinyon Wash, and all sizes less than 1/16″ were screened out.

FIG. 8.

them with 2-in. galvanized sheet-iron pipe generously perforated with $\frac{1}{16}$-in. holes. These pipes were driven so that the top was just flush with the ground surface, and they were closed at the top with wooden plugs. In some of the tanks it was found impossible to bring the ground-water surface to the desired level with the available hydrostatic pressure from the reservoir tanks, and 2-in. holes were bored between the observation holes to the saturated gravel layer. Water usually rose in these holes to the same height as in the reservoir tank, and, by seeping laterally into the soil, built up the ground-water surface. It was found difficult to keep these holes open to the gravel, however, and the water level in most of them eventually represented the ground-water surface.

Three tank sets were installed in the open valley floor east of Independence in February, 1909. The surface of Soil Tank No. 1 was bare sand; Nos. 2 and 3 (Fig. 7) were laid with salt-grass sod. The initial plan formulated for Tank Sets Nos. 1 and 3 was to hold the ground-water level at various depths below the ground surface for periods of a few weeks during the summer while the climatic conditions were constant, in order to obtain, in a short time and with few tanks, trustworthy results of a general nature. The movement of the water surface from one level to another consumed so much time, however, that winter approached before the experiments on the lower levels were reached, and furthermore, there was no accurate method of determining the volume of evaporated water represented by the differences in depth. The experience of the first year's work with these tanks showed the necessity of maintaining a fixed ground-water level during a complete cycle of climatic changes. In Soil Tank No. 2 it was at first proposed to hold the ground-water level at or near the ground surface, but so great was the rate of summer evaporation that this plan was found to be impracticable with the equipment available. To remedy the defect, the hydrostatic pressure from the reservoir tank was increased by soldering to it a 3-ft. extension, but this was not used until late in the season. This experience suggested the desirability of placing the reservoir tanks above the soil tanks and of increasing the size of the feed pipe.

As a result of these preliminary observations, four additional tank sets were installed in January, 1910. The reservoir tank outlets were placed about 1.7 ft. above the soil tank inlets, and 1-in. pipe was used

throughout. The new soil tanks were laid with salt-grass sod, which took root and grew in every tank. The general plan of operation for Tank Sets Nos. 2 to 7 was to supply the reservoir tanks with water in quantities such that the depths to ground-water in the soil tanks were, respectively, 5 ft., 4.5 ft., 4 ft., 3 ft., 2 ft., and 1 ft. Observations were carried on continuously on the six tanks during the two years, 1910

INFLUENCE OF ALTITUDE ON EVAPORATION FROM WATER SURFACE ON THE EASTERN SLOPE OF MOUNT WHITNEY, CALIFORNIA.

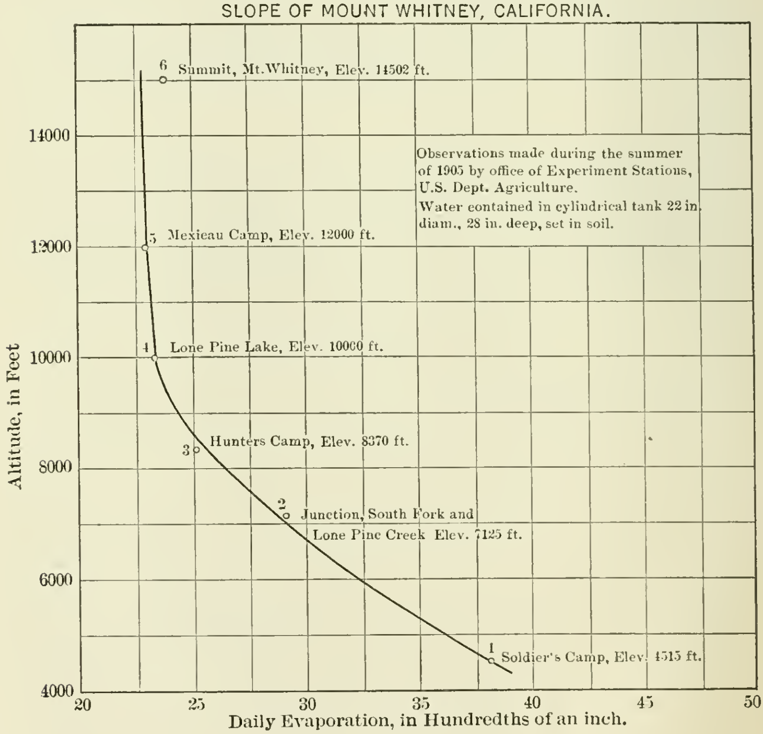


FIG. 9.

and 1911. The operation and results were quite satisfactory, with the exception that in Tank Set No. 7 the pressure from the reservoir tank was not sufficient between April and September to hold the water level at the 1-ft. depth.

An important feature of reproducing natural conditions for combined soil evaporation and transpiration is to obtain a fully developed root system reaching down to the ground-water surface. At best, this

requires more than a year, particularly for the greater depths. In order to stimulate the growth as much as possible, the water level in all soil tanks was brought up to about 1 ft. below the surface as soon after installation as possible. This was accomplished by pouring water into the observation holes until the soil was completely saturated to the level desired and the surface showed moisture. Then no water was added to the reservoir tanks until the ground-water level had receded by evaporation and transpiration to the desired level. The grass roots were thus given a good initial irrigation and an opportunity to follow the water down. Active growth occurred in Tanks Nos. 4 to 7 during the first year, and continued with greater vigor during the second year. In Tank No. 3 a less active growth occurred the first year, but the results were more satisfactory during the second year. There was practically no growth in Tank No. 2 during the first year, although the grass did not die. During the second year the grass showed more signs of life, but did not grow as actively as in Tank No. 3.

The details of the observations on soil evaporation for 1910 and 1911 for Tank Set No. 5 are shown graphically on Plate IV. The supply of water available to the soil from the reservoir tank is the element under complete control of the observer, and at the top of the diagram are statements of the purpose governing additions to or withdrawals from this supply during various periods of time. Below this is platted a broken line representing the fluctuation of water surface in the reservoir tank, the vertical portions indicating additions to or withdrawals from the reservoir supply made by the observer, and the inclined portions indicating the soil-tank draft. There is also platted a mass-curve showing the aggregate volume of water supplied to the reservoir tank, which appears as a series of vertical and horizontal lines. At the bottom of the diagram is platted an undulating line representing the fluctuation of ground-water surface in the soil tank, each depth being obtained by averaging the depths recorded in the observation holes.

The small part that precipitation plays in ground-water fluctuations in Owens Valley is shown by this diagram. The average annual precipitation at the experiment station is about 4.38 in., the season, 1909-10, being normal and 1910-11 well above normal. At the bottom of the diagram is noted the date and quantity of precipitation for each storm. It is seen that, even in a wet season, percolating water does not penetrate to depths exceeding 2.5 ft., unless more than 1 in. falls

within a short period on moist soil. Even then it does not appear to reach depths greater than 4 ft. The problem of percolation from rainfall, therefore, is practically eliminated from the experiments. When rising ground-water was noted in a soil tank after precipitation, the volume of percolating water was estimated from the observed rise and included in the mass-curve, as noted on the diagrams.

The quantity of water evaporated from the soil surface of any tank during a given period can be computed accurately from the diagrams, when the depth to ground-water at the beginning and end of the period is the same, by noting from the mass-curve the quantity supplied to the reservoir tank during the period and the accumulation or depletion in the reservoir tank. The sum of these quantities, with their proper algebraic sign, gives the loss by evaporation. For differing depths to ground-water, however, the computations are only approximate, because the proportion of empty space in the soil layer and the quantity of moisture it contained initially are both unknown. A monthly summary of results for Tank Sets Nos. 2 to 7 for 1911 is presented in Tables 9 to 14. The annual depth of evaporation from the several soil tanks exhibited a consistent decrease with increase of depth to ground-water, and varied from 48.8 in. for No. 7 to 13.43

TABLE 9.—DEPTH OF EVAPORATION FROM GROUND SURFACE NEAR INDEPENDENCE DURING 1911.

TANK SET NO. 2.

Month.	Volume of water supplied to reservoir tank, in gallons.	Depth of Water in Reservoir Tank, in Feet.		Accumulation or depletion of water in reservoir tank, in gallons.	Volume of Water Evaporated.			Average depth to ground-water surface in soil tank, in feet.
		Beginning of month.	End of month.		Total, in gallons.	Depth, in inches.	Rate, in inches per 24 hours.	
Jan........	6	1.10	1.15	+ 2	4	0.15	0.005	4.98
Feb........	0	1.15	1.11	— 1	1	0.04	0.001	4.95
Mar........	3	1.11	1.14	+ 1	2	0.07	0.002	4.94
Apr........	10	1.14	1.18	+ 1	9	0.33	0.011	4.94
May	30	1.18	1.19	0	30	1.11	0.036	4.98
June	66	1.19	1.39	+ 6	60	2.22	0.074	5.03
July	71	1.39	1.22	— 5	76	2.81	0.091	5.00
Aug.	105	1.22	1.78	+ 18	87	3.22	0.104	4.95
Sept........	52	1.78	1.52	— 8	60	2.22	0.074	4.80
Oct........	18	1.52	1.37	— 5	23	0.85	0.028	4.80
Nov........	1	1.37	1.18	— 6	7	0.26	0.009	4.85
Dec........	1	1.18	(1.10)	— 3	4	0.15	0.005	4.98
Year.....	363	1.10	1.10	0	363	13.43	0.037	4.94

TABLE 10.—Depth of Evaporation From Ground Surface Near Independence During 1911.

Tank Set No. 3.

Month.	Volume of water supplied to reservoir tank, in gallons.	Depth of Water in Reservoir Tank, in Feet.		Accumulation or depletion of water in reservoir tank, in gallons.	Volume of Water Evaporated.			Average depth to ground-water surface in soil tank, in feet.
		Beginning of month.	End of month.		Total, in gallons.	Depth, in inches.	Rate, in inches per 24 hours.	
Jan	9	0.14	0.10	− 1	10	0.37	0.012	4.53
Feb	18	1.10	0.23	+ 4	14	0.52	0.019	4.59
Mar	12	0.23	0.20	− 1	13	0.48	0.015	4.48
Apr	40	0.20	0.54	+ 11	29	1.07	0.036	4.50
May	62	0.54	0.60	+ 2	60	2.22	0.072	4.49
June	103	0.60	0.96	+ 12	91	3.37	0.112	4.63
July	160	0.96	0.67	− 9	169	6.25	0.202	4.51
Aug	285	0.67	2.00	+ 43	242	8.96	0.289	4.52
Sept	135	2.00	1.13	− 28	163	6.03	0.201	4.22
Oct	27	1.13	0.54	− 19	46	1.70	0.055	4.21
Nov	4	0.54	0.16	− 12	16	0.59	0.020	4.33
Dec	3	0.16	(0.10)	− 2	5	0.18	0.006	4.56
Year	858	0.14	0.10	0	858	31.74	0.087	4.46

TABLE 11.—Depth of Evaporation From Ground Surface Near Independence During 1911.

Tank Set No. 4.

Month.	Volume of water supplied to reservoir tank in gallons.	Depth of Water in Reservoir Tank, in Feet.		Accumulation or depletion of water in reservoir tank, in gallons.	Volume of Water Evaporated.			Average depth to ground-water surface in soil tank, in feet.
		Beginning of month.	End of month.		Total, in gallons.	Depth, in inches.	Rate, in inches per 24 hours.	
Jan	7	1.53	1.49	− 1	8	0.30	0.010	3.97
Feb	− 8	1.49	1.18	− 10	2	0.07	0.002	3.36
Mar	3	1.18	1.19	0	3	0.11	0.004	3.74
Apr	62	1.19	2.15	+ 31	31	1.15	0.038	4.00
May	96	2.15	2.57	+ 14	82	3.04	0.098	4.06
June	121	2.57	2.63	+ 2	119	4.40	0.147	(3.34)
July	114	2.63	1.97	− 21	135	5.00	0.161	3.44
Aug	141	1.97	2.47	+ 16	125	4.63	0.149	3.92
Sept	65	2.47	1.90	− 18	83	3.07	0.102	3.85
Oct	30	1.90	1.53	− 12	42	1.55	0.050	3.93
Nov	9	1.53	1.09	− 14	23	0.85	0.028	3.97
Dec	6	1.09	(0.91)	− 6	12	0.44	0.015	4.10
Year	646	1.53	0.91	− 19	665	24.61	0.067	3.81

TABLE 12.—DEPTH OF EVAPORATION FROM GROUND SURFACE NEAR INDEPENDENCE DURING 1911.

TANK SET NO. 5.

Month.	Volume of water supplied to reservoir tank, in gallons.	Depth of Water in Reservoir Tank, in Feet.		Accumulation or depletion of water in reservoir tank, in gallons.	Volume of Water Evaporated.			Average depth to ground-water surface in soil tank, in feet.
		Beginning of month.	End of month.		Total, in gallons.	Depth, in inches.	Rate, in inches per 24 hours.	
Jan........	8	2.55	2.43	— 4	12	0.44	0.014	3.01
Feb........	6	2.43	2.42	0	6	0.22	0.008	2.47
Mar........	3	2.42	2.36	— 2	5	0.18	0.006	2.73
Apr........	88	2.36	3.65	+ 42	46	1.70	0.057	2.99
May........	141	3.65	4.09	+ 14	127	4.70	0.151	3.01
June.......	166	4.09	4.19	+ 3	163	6.03	0.201	3.40
July........	244	4.19	4.14	— 2	246	9.11	0.294	3.06
Aug........	255	4.14	4.92	+ 23	232	8.58	0.280	2.99
Sept........	127	4.92	4.07	— 25	152	5.62	0.188	2.69
Oct.........	36	4.07	3.24	— 27	63	2.33	0.075	2.77
Nov........	9	3.24	3.67	— 18	27	1.00	0.033	2.83
Dec........	1	2.67	(2.45)	— 7	8	0.30	0.010	2.90
Year.....	1 084	2.55	2.45	— 3	1 087	40.21	0.110	2.90

TABLE 13.—DEPTH OF EVAPORATION FROM GROUND SURFACE NEAR INDEPENDENCE DURING 1911.

TANK SET NO. 6.

Month.	Volume of water supplied to reservoir tank, in gallons.	Depth of Water in Reservoir Tank, in Feet.		Accumulation or depletion of water in reservoir tank, in gallons.	Volume of Water Evaporated.			Average depth to ground-water surface in soil tank, in feet.
		Beginning of month.	End of month.		Total, in gallons.	Depth, in inches.	Rate, in inches per 24 hours.	
Jan........	12	3.03	3.19	+ 5	7	0.26	0.008	1.92
Feb........	9	3.19	3.17	— 1	10	0.37	0.013	1.31
Mar........	24	3.17	3.32	+ 5	19	0.70	0.023	1.70
Apr........	94	3.32	3.53	+ 7	87	3.22	0.107	2.00
May........	163	3.53	3.54	0	163	6.03	0.195	1.99
June.......	182	3.54	3.75	+ 7	175	6.48	0.216	2.30
July........	213	3.75	3.31	—14	227	8.40	0.271	2.02
Aug........	314	3.31	4.25	+30	284	10.50	0.339	2.01
Sept........	143	4.25	3.89	—12	155	5.74	0.192	1.55
Oct.........	38	3.89	3.36	—17	55	2.04	0.065	1.65
Nov........	8	3.36	2.98	—12	20	0.74	0.025	1.84
Dec........	6	2.98	(2.83)	— 5	11	0.41	0.013	2.04
Year.......	1 206	3.03	2.83	— 7	1 213	44.89	0.122	1.86

TABLE 14.—DEPTH OF EVAPORATION FROM GROUND SURFACE NEAR INDEPENDENCE DURING 1911.

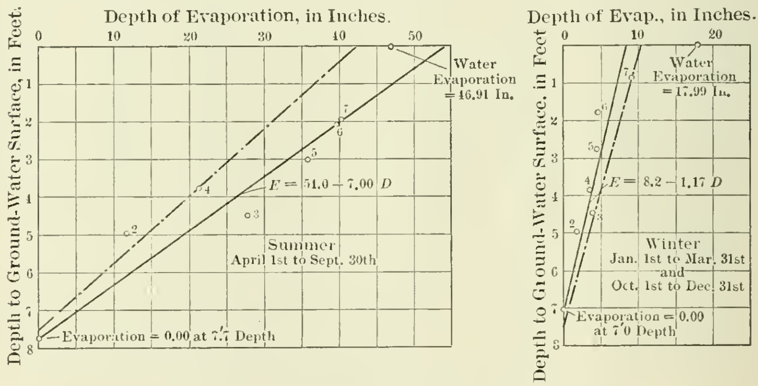
TANK SET NO. 7.

Month.	Volume of water supplied to reservoir tank, in gallons.	Depth of Water in Reservoir Tank, in Feet.		Accumulation or depletion of water in reservoir tank, in gallons.	Volume of Water Evaporated.			Average depth to ground-water surface in soil tank, in feet.
		Beginning of month.	End of month.		Total, in gallons.	Depth, in inches.	Rate, in inches per 24 hours.	
Jan	3	5.07	4.70	— 12	15	0.56	0.018	0.73
Feb	31	4.70	5.08	+ 12	19	0.70	0.025	0.81
Mar	67	5.08	5.90	+ 26	41	1.52	0.049	0.98
Apr	102	5.90	5.96	+ 2	100	3.70	0.123	1.46
May	151	5.96	5.92	— 1	152	5.62	0.181	1.64
June	160	5.92	5.62	— 10	170	6.30	0.210	2.06
July	223	5.62	5.40	— 7	230	8.52	0.275	2.19
Aug	255	5.40	5.99	+ 19	236	8.74	0.281	2.51
Sept	178	5.99	5.79	— 6	184	6.81	0.227	2.39
Oct	115	5.79	5.77	— 1	116	4.29	0.139	1.44
Nov	14	5.77	4.96	— 26	40	1.48	0.049	0.60
Dec	0	4.96	(4.50)	— 15	15	0.56	0.018	0.60
Year	1 299	5.07	4.50	— 18	1 318	48.80	0.133	1.45

in. for No. 2. The depth of summer evaporation varied from 81 to 90% of the annual in the several tanks, and averaged 87 per cent. The month of maximum evaporation is August, and minimum evaporation occurs during December to March, inclusive. The exact date of maximum evaporation rates for the several soil tanks occurs about September 1st, and they follow each other consecutively with greater depth to ground-water. The approximate dates of maximum and minimum air temperatures at Independence are July 10th and January 10th, respectively, but no measurements were made to determine the lag of corresponding soil temperatures at various depths. The extremes of evaporation from water surfaces agree in time of occurrence with maximum and minimum air temperatures, however, and the observed lag in soil evaporation is in general consistent with the observed lag in soil temperatures in other localities. Hence it is reasonable to conclude that extremes in the rate of soil evaporation and soil temperature are concurrent at a given depth.

A graphic study of the data in Tables 9 and 14 for the periods, April 1st to September 30th, and October 1st to March 31st, which are, respectively, periods of increasing and decreasing evaporation rate, is presented in Fig. 10. There appears to be, during each period,

a straight-line relation between total evaporation and depth to ground-water. The limiting depth is 7.7 ft., and the total evaporation when water and ground surface coincide, 54.0 and 8.2 in., respectively. The total depth of evaporation, in inches, being represented by E, and the depth to ground-water, in feet, by D, the equations representing variation in evaporation with depth to ground-water are $E = 54.0 - 7.00\ D$ and $E = 8.2 - 1.17\ D$. It will be noted that the combined soil evaporation and transpiration during the summer exceeded the water evaporation from the tanks in the soil by 15 per cent.



OWENS VALLEY SOIL EVAPORATION CURVES
FOR ALKALI SALT GRASS LAND
Based on Soil Tank Observations of 1911.
——— Curve based on 1911 Data.
-·-·-·- Curve based on 1910-11 Data.
o 1911 Observations.

FIG. 10.

The curve based on the 1910-11 data is shown on the diagram for comparison. There was a marked increase in total evaporation during 1911, as compared with the season, 1910-11, which was due to the more complete development of the root systems. Broadly speaking, the results for 1911 showed an increase of 17% in the volume of water consumed during the two periods. A continuation of observations for another year would show still further increase for those tanks in which the grass roots had not reached the water plane. Observations of depth to water in test holes in the transition zone between meadow and desert land indicate that soil evaporation ceases for depths exceeding 8 ft. The effect of increased evaporation for the tanks with greatest depth to ground-water would be to drop the lower end of the

curve to some point below 7.7 ft. The true curve, therefore, is probably steeper than that for 1911, crossing the X-axis at about the same point, but the Y-axis at about 8 ft. instead of 7.7 ft. However, in the practical use of the curve, the departure of the lower end from the true position does not affect materially the computations of the total volume of water evaporating from a given area, as the proportion of such volume originating in areas of relatively deep ground-water is small.

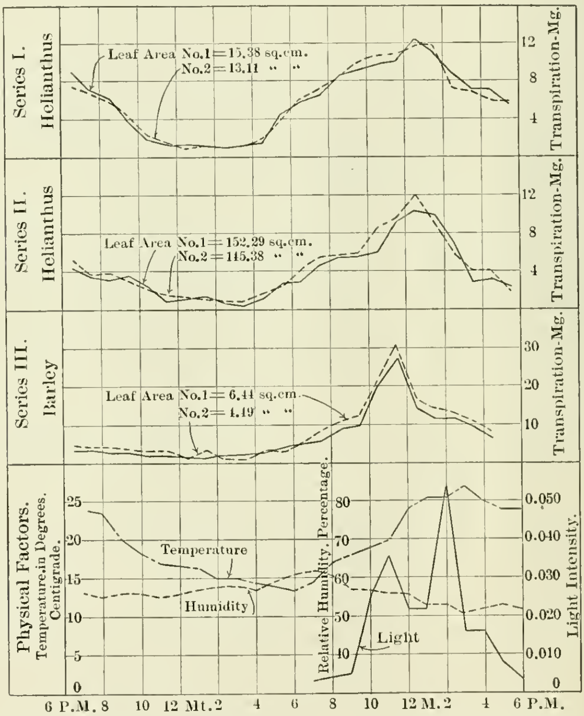
Transpiration.—A considerable portion of the water evaporating from the soil is absorbed by plant roots and carried upward through the stem and into the foliage, whence it escapes in the process of transpiration. This process continues as long as the plant has life, but is most active during the growing period. Transpiration differs in different species of plants, and even in the same species when existing under different conditions of light, atmospheric pressure, soil texture, and available moisture in the soil. King's experiments indicate that humidity does not affect transpiration.* For a species growing in a definite locality, light and available soil moisture are the controlling factors.

The process of transpiration and respiration in plants is similar to the breathing of animals. Both plants and animals inhale air and exhale from the respiratory organs large quantities of water. The lungs of animals are intended primarily to provide a means for the entrance of oxygen into the body and for the escape of carbon dioxide, but they cannot perform their functions unless the interior lining of the air cells is kept moist. Similarly, the breathing surface of a plant must be kept moist, and, as a protection from too rapid evaporation, this surface is within the plant structure, principally in the foliage. Plant leaves are enclosed in a relatively impervious skin or epidermis in which are small breathing pores or stomata which open or close automatically, depending on the needs of the plant for a greater or less quantity of air. When exposed to light, the food-manufacturing processes of a green plant are stimulated, and require a continually changing volume of air in contact with the breathing surface. The stomata open proportionally to the light intensity. Should the water supply in contact with the roots be insufficient, the breathing surface may become dry, and when that happens the stomata close automatically

* "Irrigation and Drainage," by F. H. King, New York, 1899.

until the proper quantity of air is admitted for the plant to do its work under the new conditions. The stomata, therefore, control the quantity and rate of loss of water from plants by transpiration.

There is a marked diurnal periodicity in the rate of transpiration, which investigators are led to believe is largely the result of the varying intensity of light. This periodicity is well illustrated by ob-



RELATION OF TRANSPIRATION TO LIGHT INTENSITY DURING A 24-HOUR DAY.

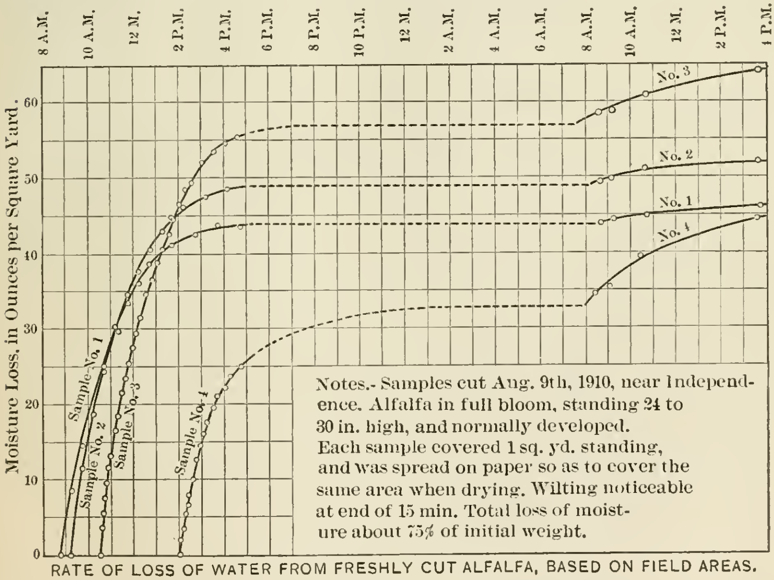
FIG. 11.

servations made under the direction of Mr. Frederick E. Clements, State Botanist of Minnesota, and reproduced in Fig. 11.* Measurements of transpiration were made hourly from 6 P. M. on February 16th to 6 P. M. on February 17th, and the physical factors were observed between these hours. The day was cloudy throughout, so that

* "Influence of Physical Factors on Transpiration", by A. W. Sampson and L. M. Allen, Minnesota Bot. Studies, Pt. I, Vol. 4, 1909, p. 42.

the variation in temperature and humidity was slight. The diagrams show very strikingly the response of transpiration to changes in intensity of light.

No measurements of transpiration are available for conditions similar as regards altitude and aridity to those in Owens Valley. It is unnecessary in this study to know separately the transpiration from wild grasses and the evaporation from bare soil, because the area of the latter is relatively small. The experiments on soil evaporation, therefore, were planned to give the combined loss from these two causes. It is desirable, however, to know the quantity of transpiration from field crops, in order to aid in computing the quantity of percolation from irrigation. Observations for such crops were confined to alfalfa.



RATE OF LOSS OF WATER FROM FRESHLY CUT ALFALFA, BASED ON FIELD AREAS.

FIG. 12.

The method of measurement was based on the assumption that the rate of loss of water from freshly cut plants would correspond closely to the rate before cutting. The plants were cut rapidly from a measured area, weighed, and spread out on paper to cover the same area as before cutting. At short intervals they were reweighed until there was no further appreciable loss. No noticeable wilting occurred during the first 15 min. and the rate of loss during this period was used as

a basis for calculations. The results of the measurements are shown graphically in Fig. 12.

The rapid decrease in the rate of loss is very noticeable. Inspection of Fig. 11 will show that the rates of transpiration at 8.45, 9.15, and 10.30 A. M., and 2.02 P. M., expressed as percentages of the average rate for 24 hours, are, respectively, 128, 141, 177, and 197, an average of 161 per cent. If a similar relation is assumed, the average loss in a 24-hour day from the four alfalfa samples would be 366 oz. per sq. yd. of field area, or 0.49 in. in depth. This figure appears to be rather large, at first glance, for the rate of evaporation for that day from the pan in Owens River was 0.30 in., and that from the shallow pan in the soil was 0.38 in. The results obtained by German investigators indicate the loss from sod during the growing season to be 92% greater than from water surface, and that from cereals to be 73% greater. Furthermore, the humidity of the air after passing over an alfalfa field is very noticeably greater than after crossing a body of water. The result obtained in the experiment here described, therefore, is within reason.

The growing season for alfalfa in the vicinity of Independence is marked by an entire absence of cloudiness. It extends from about April 15th to September 30th, during which time three crops mature, the yield being about 5 tons of dry matter to the acre. The samples used for the experiments were almost ready for the second cutting. On the assumption that the average area of transpiring surface during the entire growing season was 50% of that on the day of the experiment, the total loss of water during the season would amount to 41 in., or 3.43 ft. in depth. Therefore, with a production of dry hay, amounting to 5 tons to the acre, there would be 1 lb. of dry matter for every 935 lb. of water lost by transpiration.

Ground-Water.

Form of the Ground-Water Surface.—The general form of the ground-water surface corresponds with that of the surface of the valley fill, although the slopes are less steep and the irregularities are not so pronounced. In the valley floor the depth to ground-water is only a few feet. It becomes progressively greater toward the mountains, and probably lies 200 or 300 ft. beneath the outwash slope at about the 5 000-ft. contour. Superimposed on the general ground-water surface are sharp "ridges" beneath stream channels and "mounds" under irrigated

fields. The surface of the water in the underground reservoir, therefore, is not a level plain, but has a varied topography.

There are two reasons for this condition: the action of gravity tending to equalize inequalities in the ground-water surface, and the resistance which the ground offers to the lateral motion of water through its interstices. Percolating waters enter the valley fill from the upper edge of the outwash slope, from stream channels crossing the outwash slope, and from irrigated fields. The valley floor is the lowest portion of the valley fill and also the ground-water outlet. The force of gravity, therefore, tends to draw percolating water which has reached the surface saturation to the level of the valley floor. This can occur only by a lateral movement of water from the outwash slope toward the valley floor, but the resistance of the porous material is so great that a steep gradient is necessary to maintain even a very low velocity. Hence there is the steep slope of the ground-water surface from the mountains toward the valley, at many points exceeding 80 ft. per mile, and laterally from stream channels and irrigated fields. The lateral movement of the water is so slow that percolating water, entering at the upper edge of the outwash slopes, does not reach the valley for at least 2 years.

In order to outline the ground-water definitely, all existing domestic wells in the region were located and many additional observation wells were drilled, where the cost was not prohibitive. The region contains 27 domestic wells, 12 of which are on the valley floor and 15 on the outwash slopes. There were drilled in addition 142 observation wells, all but two being on the valley floor. These wells were sufficient to define the ground-water surface over about 60 sq. miles of the region.

Ground-water contours for the valley floor showing lines of equal average depth to ground-water have been worked out on Plate V. They represent the average position of the surface of saturation between the annual extremes. The data are sufficient to determine the 3-, 4-, and 8-ft. contours with reasonable accuracy. The sudden approach of ground-water toward the surface at the upper edge of the grass land is shown, and also the general proximity of ground-water to the surface throughout the valley floor. The total area between the westerly 8-ft. contour and Owens River is 67 sq. miles. The average depth to ground-water is between 4 and 8 ft. over 40% of this area, and between 3 and 4 ft. over 28 per cent. It exceeds 8 ft. over 14% of the area, and is 3 ft. or less over 18 per cent. The area of the valley floor is 66.4 sq. miles

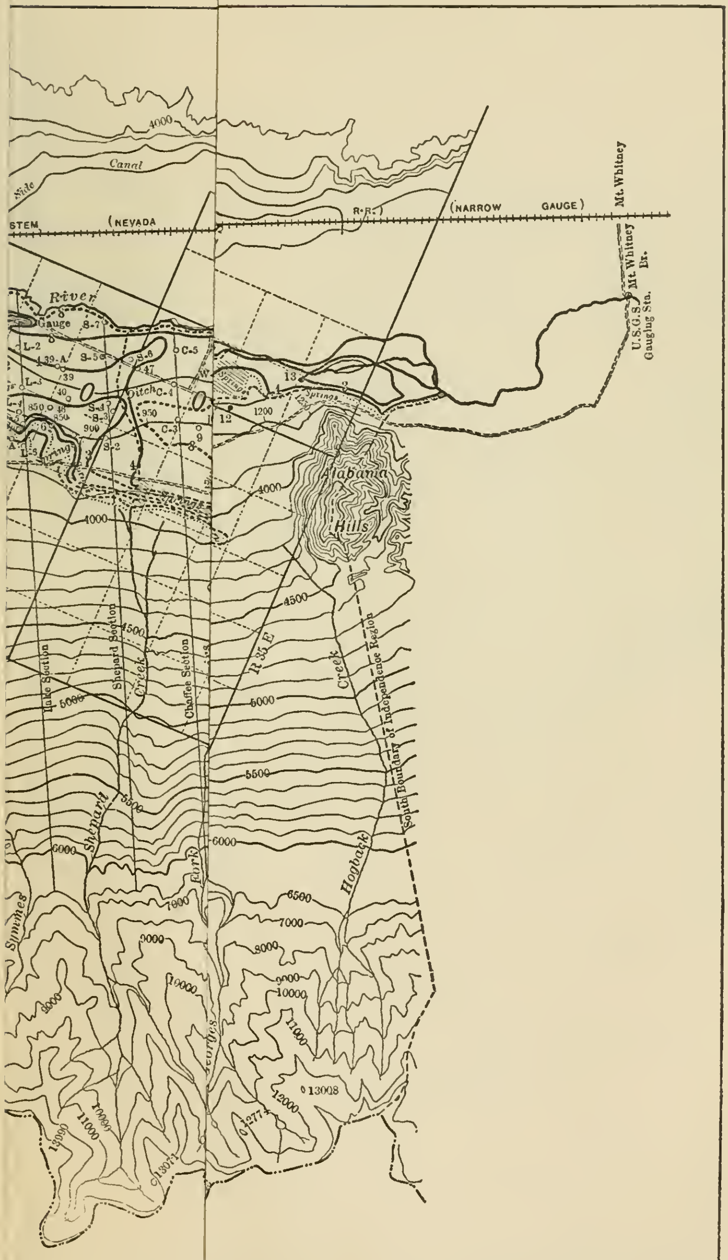
(Table 1), and its west boundary practically coincides with the 8-ft. contour.

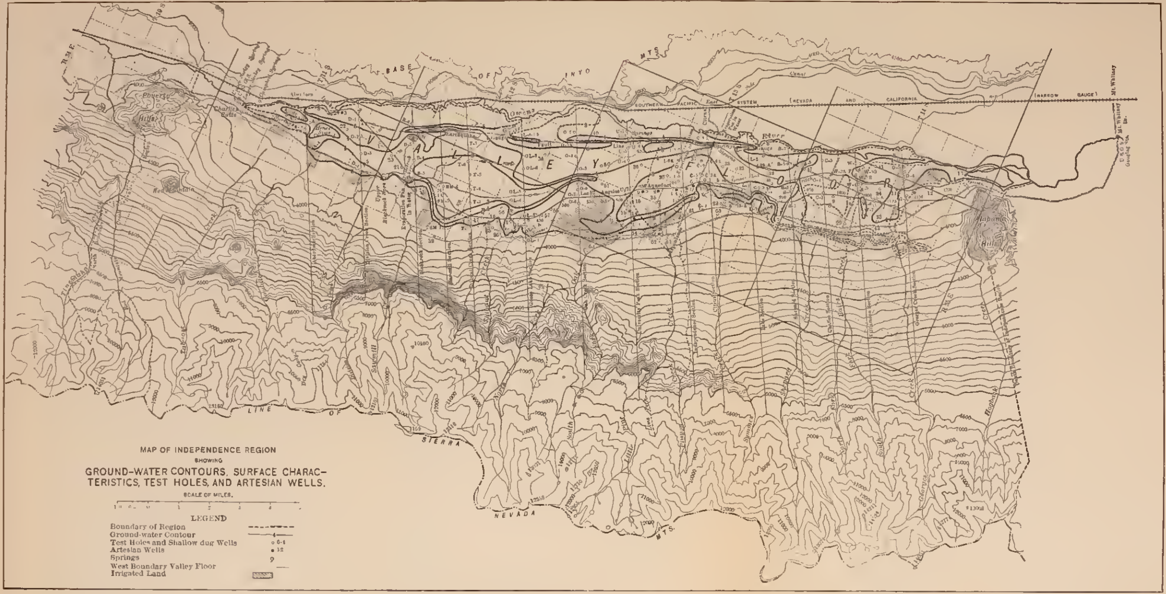
There is a very striking relation between vegetation and depth to ground-water. On the outwash slopes the vegetation consists of various stunted desert shrubs. In approaching the valley floor at about the 20-ft. contour, sagebrush begins to predominate, and has a luxuriant growth as far east as the 12-ft. contour, where it is replaced by greasewood, rabbit brush, and coarse bunch grass. In the vicinity of the 8-ft. contour, salt grass begins to appear, and farther east, near and within the area inclosed by the 4-ft. contour, it grows luxuriantly. Within the 3-ft. contour, fresh-water grasses thrive where there is sufficient surface water to leach out and carry away most of the alkali, but the salt grass grows well, even where the soil is alkaline. In various portions of the valley floor rabbit brush and greasewood are found where the average depth to ground-water is 4 ft. or more, but grass predominates east of the 8-ft. contour. In areas where the alkali is excessive there is practically no vegetation. In general, grass does not grow where the depth to ground-water exceeds 8 ft., so the 8-ft. contour tends to coincide with the boundaries between meadow and desert lands.

Fluctuation of the Ground-Water Surface.—The surface of the ground-water is continually fluctuating. Both the extent and character of this fluctuation vary widely in different localities and at different times, depending on the proximity to ground-water sources or outlets and the relative rates of ground-water accretion and depletion. Three pronounced types are to be observed in the Independence Basin: (1) broad irregular fluctuations of varying amplitude in the outwash-slope area; (2) slightly irregular periodic fluctuation with wide fixed limits in and near irrigated areas; and (3) a regular periodic fluctuation with comparatively narrow and fixed limits in the valley floor. Special characteristics are also exhibited by wells within certain limited areas, as the result of local ground-water conditions.

These fluctuations were determined and studied from well observations made by the methods already described. Readings obtained at intervals of from 2 to 4 weeks were sufficient to establish accurately the position of the ground-water surface, as the fluctuations are characterized by great regularity. Most of the wells were observed from August 15th, 1908, to November 15th, 1909, and on 26 of the most

PLATE V.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.




BASE OF INYO MTS
SOUTHERN PACIFIC
NEVADA AND CALIFORNIA
VALLEY FLOOR
Owens River
Charlies Butte
Poverty Hills
Red Mountain
Tinemaha Res.
Sawmill
Oak
North
South
Little
Pine
Thibaut
Symmes
Shepherd
Bairs
George
Hogback
Creek
Independence
Mt. Whitney
LINE OF SIERRA NEVADA MTS.
MAP OF INDEPENDENCE REGION
SHOWING
GROUND-WATER CONTOURS, SURFACE CHARACTERISTICS, TEST HOLES, AND ARTESIAN WELLS.
SCALE OF MILES.
LEGEND
Boundary of Region
Ground-water Contour
Test Holes and Shallow dug Wells
Artesian Wells
Springs
West Boundary Valley Floor
Irrigated Land

typical wells observations were continued to May 1st, 1911. The fluctuation of the surface of the lake south of Citrus Bridge was observed from August 15th, 1908, to November 15th, 1909, and of Goose Lake from August 15th, 1908, to May 1st, 1911.

The type of fluctuation peculiar to wells on the outwash slope is shown on Plate VI by Wells Nos. 31, 64, 25, 26, and 59, and Citrus No. 1. Water stands 10 ft. or more below the surface in all these wells, the vegetation of the surrounding area is limited to desert shrubs. and there are no alkali deposits on the surface. With knowledge of the sources and movements of ground-water beneath the outwash slopes, the assigned cause for this type would be annual variation in the quantity of water supplied by percolation from precipitation on the intermediate and outwash slopes and from stream channels. This is confirmed by the observations. For example, Well No. 31, which is 7 miles from the base of the Sierra and 500 ft. south of the old channel of Pinyon Creek, exhibits a persistent downward tendency which was partly checked during the summer of 1909 and 1910. The maximum effect of the very wet years, 1906 and 1907, evidently reached this well in 1908 and early in 1909. During the following years the water had a tendency to return to its normal level. This was twice opposed by percolation from the channel of Pinyon Creek, which carried flood-water during a few weeks in June and July, 1909, and for a very short period in 1910. Citrus Well No. 1, which is about ¾ mile south of Well No. 31, has similar fluctuations, but in it the maximum effect of seepage from Pinyon Creek is registered 6 weeks later in 1909, and in 1910 is much smaller in quantity. Well No. 64, situated similarly with respect to the mountains, but north of Little Pine Creek, has the same downward tendency, which is checked temporarily during the summer by irrigation in a near-by alfalfa field and a small garden at the well. Well No. 59, which is 2 miles from the base of the Sierra and ½ mile south of Sawmill Creek, had an upward tendency during 1909, due to the percolation from precipitation of the wet winter, 1908-09. In 1910 the water level fell in response to the normal winter of 1909-10. Seepage from Sawmill Creek does not affect this well appreciably. Wells Nos. 25 and 26 exhibit the general tendencies of Well No. 59, but they are in the transition zone between the outwash slope and the valley floor, where there is a periodic back-water effect from the annual rise of ground-water in the grass land.

Wells Nos. 61 and 62 illustrate the type of fluctuation characteristic of the irrigated areas of the region. They are in irrigated gardens in the Town of Independence. The form of the curve is periodic, with sharp crests and troughs, the former in July, the latter in January or February. The fluctuation in such wells ranges from 10 to 20 ft. in different portions of the basin. Irregularities superimposed on the broad periodic curve are the result of irregularity in the application of irrigation water.

The fluctuation of the ground-water surface in various parts of the valley floor, other than at the eight wells already mentioned, is shown by 48 typical well records on Plate VI.

Permanent bench-marks were established at each well, and test holes from which measurements to the water surface could easily be made with a steel tape. Before observing, a weight is fastened at the end and the tape is chalked. The end of the tape is then submerged and the difference between the readings at the bench and at the water surface is the depth. Corrections are made in the office when the bench is not at the ground surface. Readings are to feet and hundredths.

Most of these wells are where the average depth to ground-water is less than 8 ft. The adjoining ground surface is more or less crusted with alkali, and, where the alkali is not too concentrated, several species of wild grass grow vigorously. The two lakes and Wells Nos. C-3 and 43 are in areas where the average depth to ground-water exceeds 8 ft., and desert conditions prevail.

The fluctuations observed in all the valley-floor wells are remarkably uniform. When platted, the observations give smooth and regular curves with an annual periodicity. The average time of occurrence of crests for wells in grass or alkali areas is March 28th; the troughs occur on September 20th, 6 months later. Heavy winter precipitation, or the proximity of springs, advances the crests into January or February, but, in the desert areas, the crest lags into April or May. The fluctuation between maximum and minimum levels in normally situated wells ranges from 1.5 to 4 ft. Wells which are near or below springs in the vicinity of intermittently occurring surface water have a greater range, which may reach 7 ft. The average fluctuation for 1908-09, as observed in 122 wells distributed generally over the valley floor, is 3.14 ft. This average represents normal conditions.

PLATE VI.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.

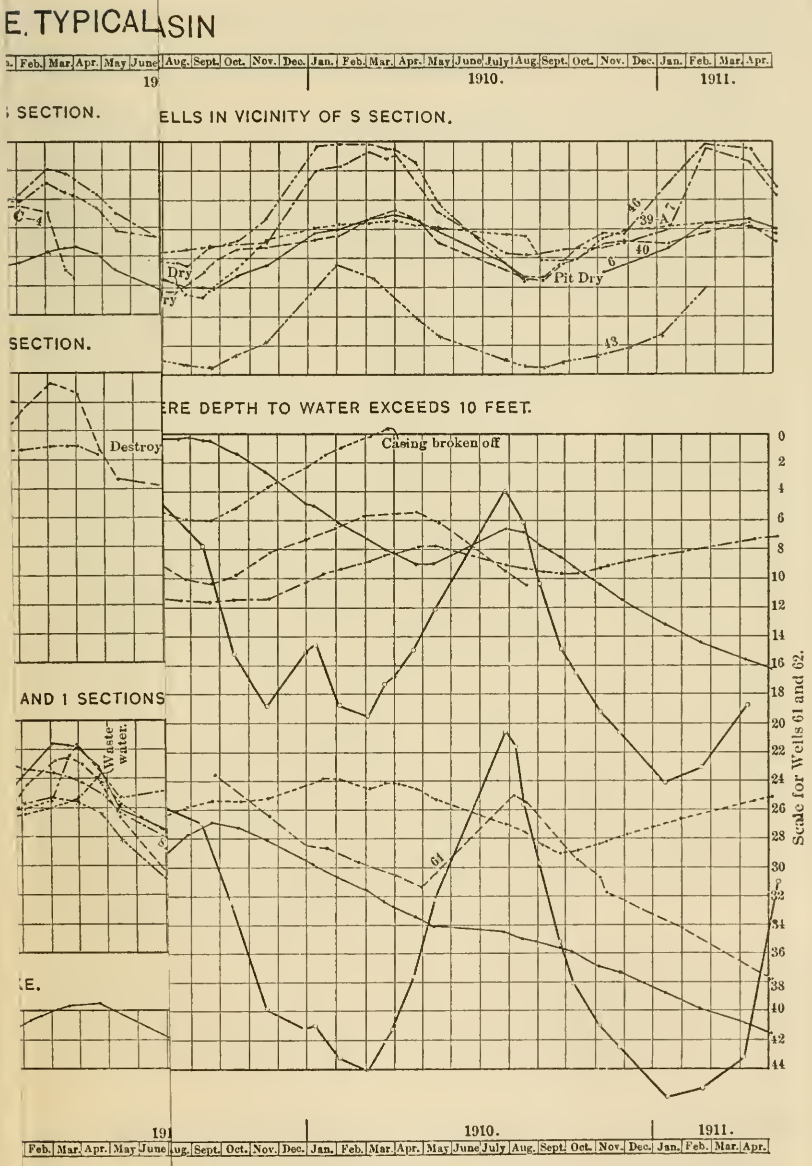
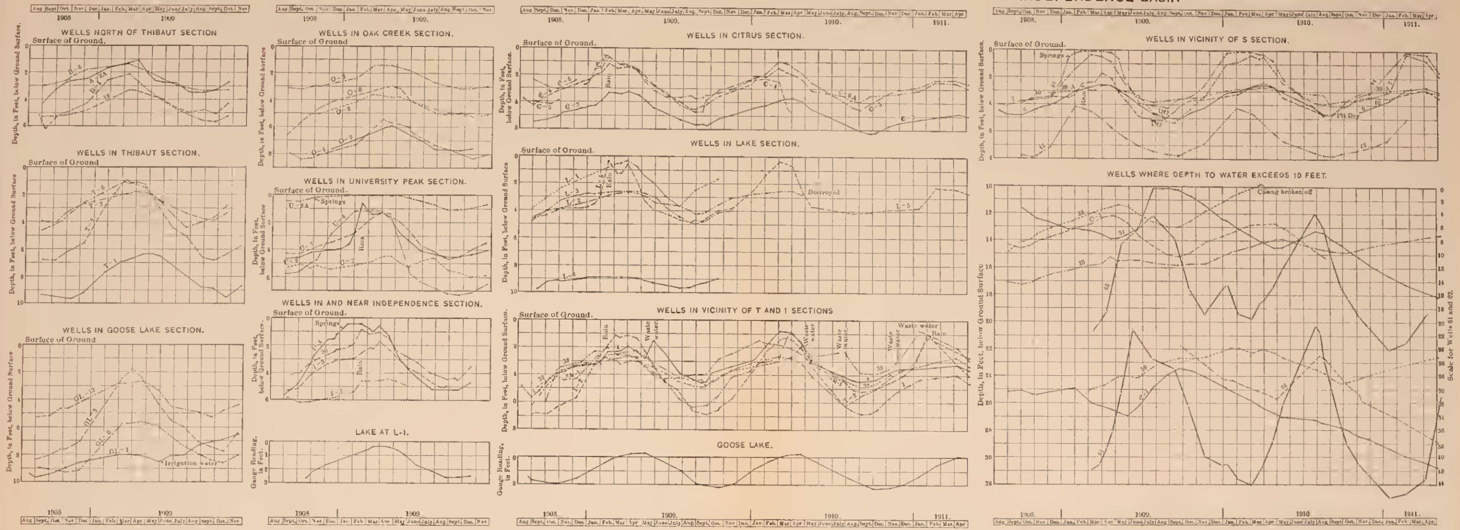


PLATE VI.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.

DIAGRAMS SHOWING FLUCTUATION OF GROUND-WATER SURFACE. TYPICAL OBSERVATION WELLS IN INDEPENDENCE BASIN



Fluctuation of this type is due to evaporation from the soil and transpiration, processes which are active wherever there is capillary connection between the surface of saturation and the ground surface, or wherever gravity water or capillary water is within reach of plant roots. Two facts have led to this conclusion: (1) the area characterized by capillary connection between ground-water surface and ground surface and by accessibility of ground-water to plant roots is coincident with the area exhibiting this type of periodic fluctuation; and (2) the combined rates of evaporation from soil and transpiration, as observed experimentally, increase and decrease concurrently and in the same ratio with the fall and rise of the ground-water surface.

The first of these facts is indicated by the following observations: Surface incrustations of alkali are now known among investigators to be an indication of evaporation from the soil, and a growth of natural grasses certainly shows the presence of water within reach of plant roots. These manifestations are both strictly confined to valley-floor areas within which the periodic fluctuation is observed. There are valley-floor areas, however, within which the periodic fluctuation occurs, but which have a loose sandy surface devoid of alkali and vegetation. An examination of such areas shows that they are surrounded or bordered by meadow and alkali-crusted land, and further that maximum and minimum ground-water levels exhibit a lag in time of occurrence which varies with the distance from these adjoining lands. (See Plate VI, Well C-3 and Goose Lake.) The fluctuations in these desert areas do not originate within the areas themselves but in the near-by lands, from which they are propagated as annual waves. In general, average depths to ground-water exceed 8 ft. in desert areas but are less than 8 ft. in meadow or alkali lands.

The second fact—that variations of soil evaporation and transpiration are similar to ground-water fluctuations—is indicated by the results of the experiments on evaporation from soil. The maximum rate of soil evaporation occurs about September 1st and the minimum from December 1st to April 1st. The lowest ground-water level occurs about September 20th and the highest level on March 28th (Plate VII). Thus the critical points in the curves of soil evaporation and ground-water fluctuation are practically coincident as regards time. Furthermore, although the curves are inversely related, their form is remarkably similar. The obvious conclusion is that ground-water fluctuations

in non-irrigated portions of the valley fill are the result of evaporation from the soil and transpiration.

Variations from the normal periodic curves occur for three causes: large precipitation, seepage from springs, and seepage from standing or flowing surface water. The infrequency of precipitation sufficient to raise the ground-water surface is shown on Plates VI and VII. It is practically a negligible factor in ground-water fluctuations. The springs at the upper edge of the outwash slope affect ground-water conditions in their vicinity by stimulating the annual rise and maintaining the ground-water level at a maximum during several months prior to March. (See Plate VI, Wells Nos. 46, U-6A, and I-4.) This results from the decrease in the rate of soil evaporation which allows the accumulation of their discharge in the surrounding soil at a greater rate than in adjoining areas where the rate of supply of underground water is less. Surface water has its source in large springs, waste from irrigation, and the flood waters of mountain streams. It occurs at various times and places, and cannot be considered as a permanent factor in ground-water fluctuations. (See Plate VI, Wells Nos. 4, 38, 39-A, 32, and GL-1.) The irregular fluctuations of ground-water on the outwash slope do not appear in the valley floor because of the relief afforded by the escape of water in springs at the upper edge of the grass land.

Ground-Water Losses.—Ground-water fluctuations within the valley floor consist primarily of the regular annual rise and fall produced by variation in the rate of evaporation. This is indicated by actual observations extending over 3 years, and confirmed by the persistency of various perennial plant species. Hence there must be overflow of ground-water from the valley fill of the region equal to the average inflow by percolation. The possible outlets would seem to be underflow southward through the valley fill, underflow by way of deep fissures, seepage and spring flow into the channel of Owens River, evaporation from spring waters, evaporation from damp soil, and transpiration from vegetation. The first two of these are eliminated by the geology and topography of the region. The slope of the ground-water surface in the valley fill opposite the Alabama Hills does not exceed 8 ft. to the mile, and the material is fine sand and clay, as indicated by the Southern Pacific Company's well at Lone Pine Station. Even if there is a movement of ground-water southward from the

PLATE VII.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.

FLUCTUDENCE.

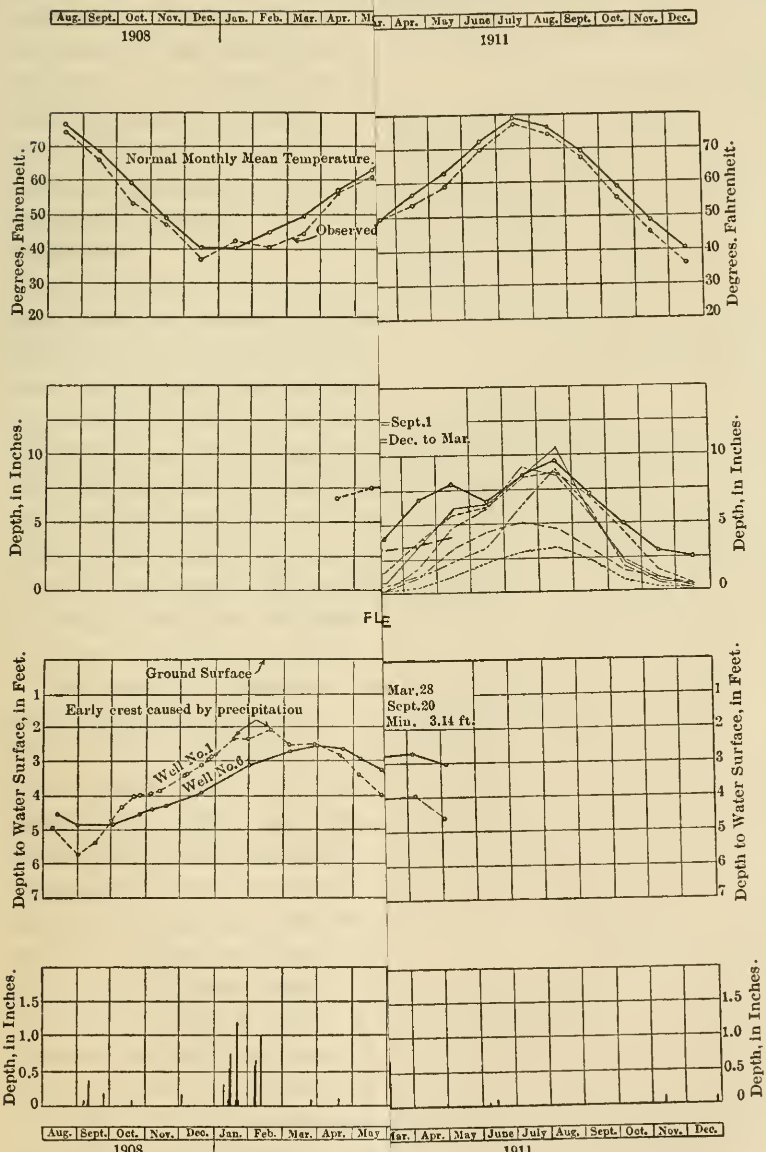
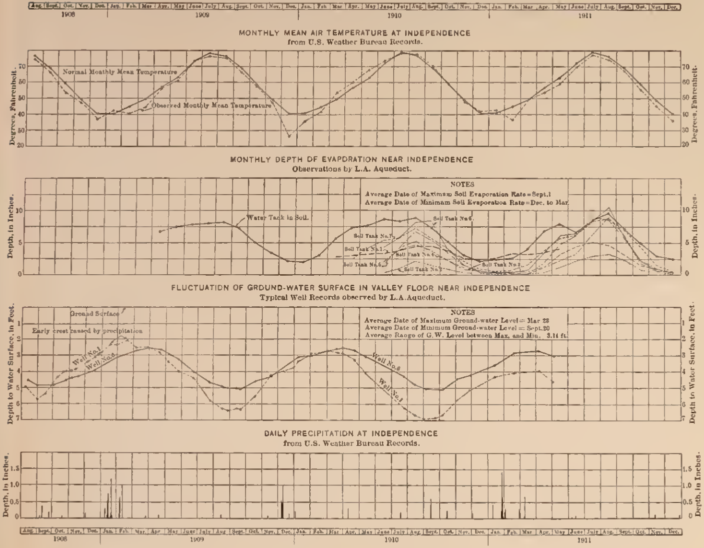


PLATE VII.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.

TEMPERATURE, EVAPORATION FROM SOIL, PRECIPITATION AND FLUCTUATION OF GROUND-WATER SURFACE IN VALLEY FLOOR NEAR INDEPENDENCE.



region, it must be exceedingly slow, and it would be entirely intercepted by the alluvial fan of Lone Pine Creek, which has a ground-water surface higher than the valley fill to the north. The granitic formation of the Sierra Nevada and the granite core of the Inyo Mountains are complete barriers against the escape of underground waters through any formation but the valley fill. It has already been shown that there is no seepage flow into Owens River from the water supply of the region. Hence the outlets by evaporation, transpiration, and spring discharge into Owens River are all that remain to be considered.

Soil evaporation and transpiration will be considered, first, for irrigated lands, and second, for the general grass and alkali area of the valley floor. The quantity of water used in irrigating the 3 011 acres under cultivation in the region is about 72 sec-ft. of continuous flow for 6 months (Table 18), which is equivalent to a depth of 8.6 ft. over the whole area. The depth of transpiration from alfalfa during the irrigating season has already been computed as 3.43 ft., or 40% of the total volume used. There is also a small loss through evaporation from the soil during and immediately after irrigations, say 0.85 ft., or 10% of the total. The total loss by evaporation from the soil and by transpiration from irrigated areas, therefore, is 4.3 ft. in depth, or 18 sec-ft., of continuous flow.

The bases for computing the evaporation and transpiration loss from grass and alkali land are the soil-evaporation equations of Fig. 10 and the ground-water contours of Plate V. The equations were developed for a fixed ground-water surface, but they cover the periods from October 1st to March 31st and from April 1st to September 30th, which practically coincide with the observed periods of rising and falling ground-water. Hence, to cover the natural conditions of fluctuating ground-water surface, average annual depth to ground-water at a given point may be substituted in the equations instead of fixed ground-water depths. The average annual depth to ground-water, in feet, and the depth of evaporation, as determined from the equations for 1911, are given in Table 15 for the non-irrigated areas enclosed by the 3-ft. contour and between the 3- and 4-ft. and 4- and 8-ft. contours. The volume annually evaporating from the whole area enclosed by these contours is equivalent to a continuous flow for the year of 109 sec-ft.

TABLE 15.—Total Evaporation From Grass and Alkali Lands in the Valley Floor.

(Based on 1911 Data.)

Enclosing contours.	Area, in square miles.	Average depth to ground-water, in feet.	Annual Depth of Evaporation, in Inches.			Equivalent flow, in second-feet.
			Summer.	Winter.	Total.	
· 3 Ft.........	11.89	2.5	36.5	5.2	41.7	36.6
3–4 Ft.........	17.66	3.5	29.6	4.0	33.6	43.7
4–8 Ft.........	25.04	5.5	15.6	0.2	15.8	29.1
Totals.......	54.59	....	....	....	....	109.4

The water of Blackrock and Hines Springs, and of the small springs along the upper edge of the valley floor, spreads out in many shallow lake basins before reaching Owens River. The loss by evaporation from the surface of these lakes is large. Estimates based on the area of water surface exposed and the evaporation from water in the shallow pan in soil indicate that about 50% of the flow of these springs thus escapes into the atmosphere. As the combined flow is 31 sec-ft., the loss by evaporation from the free water surface is 15 sec-ft. The portion of the remainder which does not flow into Owens River percolates into the soil and escapes by evaporation from the soil and by transpiration.

Two springs derive their waters from percolation and discharge directly into Owens River; these are Upper and Lower Seeley Springs. Their combined average flow is 11 sec-ft. In addition, the Blackrock Springs discharge an average of 7 sec-ft. into the river during November to March, inclusive, which is equivalent to a continuous flow of 3 sec-ft. The total discharge into the river from springs, therefore, is 14 sec-ft.

The grand total ground-water losses, therefore, are 156 annual sec-ft., of which 127 sec-ft., or 81%, is by soil evaporation and transpiration.

Rate of Recharge by Percolation.

From Precipitation.—All portions of the region receive precipitation, but there is wide local variation in the quantities which enter the ground and percolate downward to the surface of saturation. The impervious rock surfaces of the high mountain drainage areas shed

all precipitation which they receive except that lost by evaporation, but accretions to the ground-water from precipitation on the remaining areas of the region are of considerable importance.

Conditions are exceptionally favorable for percolation on the intermediate mountain slopes. As has been stated, the formation is very porous, and practically none of the run-off reaches living streams. All precipitation but that lost by evaporation, therefore, can be considered as percolating downward to the surface of saturation and becoming a permanent addition to the ground-water supply. Snow is practically all melted before May 15th, so that the period of direct exposure to evaporation is not as long as at higher levels, although the rate is greater. Evaporation losses from the moist soil are very small. Before it is melted, the snow blanket protects the soil surface, and by its gradual and uninterrupted melting it fills the capillary spaces to considerable depth, so that gravity water passes downward rapidly. When the snow disappears the rapid drying of the soil surface soon interrupts upward capillary movement, thus preventing further evaporation loss and allowing the percolating water to reach the surface of saturation. In view of these facts, the percolation factor is regarded as being about 0.75 for the more elevated areas receiving approximately 20 in. of precipitation. Less favored areas were assigned smaller factors after a study of their individual characteristics.

The results of computations of the total quantity of percolating water yielded by the intermediate mountain slopes are shown in Table 16. The method was to determine the mean seasonal precipitation at the center of area of each triangular subdivision, multiply this by the area in square miles, and apply a percolation factor. The area of each subdivision and the horizontal and vertical position of its center were obtained from Table 3. Diagrams 7, 8, 10, 11, 13, and 14 on Plate II were used in determining the depth of precipitation. The values differed slightly, as read from the altitude and distance diagrams, and the average was adopted as the most reliable. The total volume of precipitation on the 29.4 sq. miles of intermediate mountain slope is 27 580 acre-ft., of which 19 700 acre-ft. is a permanent addition to the underground water supply of the region. Expressed as a continuous flow, the total percolation from this area is 27 sec-ft.

The outwash slopes yield to the underground supply a much smaller volume of water, which is derived principally from slopes above

TABLE 16.—PERCOLATION FROM PRECIPITATION UPON INTERMEDIATE MOUNTAIN SLOPES OF INDEPENDENCE REGION.

(Mean seasonal values.)

TABOOSE GROUP OF PRECIPITATION GAUGES.

Adjoining high mountain drainage area.	Depth of Precipitation on Center of Area, in Inches.* A.	B.	Average.	Volume of precipitation on area, in acre-feet.	Percolation factor.	Quantity of Percolation. Volume, in acre-feet.	Discharge, in second-feet.
Tinemaha	22.2	17.8	20.0	2 320	0.75	1 740	2.4
Red Mountain	23.6	17.8	20.7	2 620	0.75	1 970	2.7
Taboose	22.2	16.5	19.4	4 080	0.75	3 060	4.2
Goodale	18.5	20.0	19.2	2 350	0.75	1 760	2.4
Division	19.9	15.5	17.7	900	0.70	630	0.9
	....	....	....	12 270	....	9 160	12.6
OAK GROUP OF PRECIPITATION GAUGES.							
Sawmill	18.2	18.4	18.3	1 290	0.70	900	1.2
Thibaut, North Fork	18.2	18.9	18.6	530	0.70	370	0.5
Thibaut, South Fork	14.5	15.0	14.8	60	0.60	40	0.1
Oak, North Fork	16.4	14.2	15.3	2 950	0.60	1 770	2.4
Oak, South Fork	16.4	15.8	16.1	880	0.70	620	0.9
Little Pine	17.7	15.8	16.8	1 810	0.70	1 270	1.8
Pinyon	18.7	20.8	19.8	3 050	0.75	2 290	3.2
	....	....	....	10 570	....	7 260	10.1
BAIRS GROUP OF PRECIPITATION GAUGES.							
Symmes	13.4	17.0	15.2	340	0.70	240	0.3
Shepard	12.7	12.4	12.6	650	0.65	420	0.6
Bairs, North Fork	12.4	10.8	11.6	300	0.65	200	0.3
Bairs, South Fork	14.8	12.0	13.4	860	0.70	600	0.8
George	15.8	15.8	15.8	1 760	0.70	1 230	1.7
Hogback	15.2	13.6	14.4	830	0.70	580	0.8
	....	....	....	4 740	....	3 270	4.5
Grand total	....	....	....	27 580	....	19 690	27.2

* Depth of precipitation as obtained by the precipitation-altitude diagram is given under A; as obtained by the precipitation-distance diagram under B. The average is taken for use in computations.

the 5 500-ft. contour. Precipitation occurs as snow less often here than on the higher slopes, and usually melts within a few days after falling. The capillary water in the upper layers of the soil thus has opportunity to evaporate after each storm, and it is only when several storms occur in succession that there is enough percolating water to

penetrate the ground beyond possibility of return. The long dry summer and the desert conditions draw all moisture from the ground to considerable depths, and the progress of percolating waters is slow because the capillary spaces must be refilled. Test pits dug in the region of the 4 500-ft. contour, 10 days after a series of storms, showed a penetration of capillary water to a depth of 4 ft. and the entire absence of gravity water. The total precipitation from these storms at this point was about 3.5 in., which, with a 28% available pore space, would represent 1 ft. of completely saturated soil. Considering the evaporation losses, it is not surprising that there was no gravity water within the depth of penetration observed. Observations made at higher elevations after this storm showed gravity water in considerable quantity at a depth of 12 ft. Percolation factors varying from zero to 0.60 were assigned to the several zones of the outwash slope as a result of these field observations.

The results of computations for the total quantity of percolating water yielded by the outwash slopes are shown in Table 17. The whole area of 165 sq. miles was divided into zones lying between contours at 500-ft. intervals from about 4 000 to 6 500 ft., and the zones in turn were divided into groups corresponding with the precipitation gauges. The method of computation was to average the precipitations for adjacent contours obtained from Diagrams 7, 8, 10, 11, 13, and 14 of Plate II. These averages represented the average precipitation for each zone in each group, and, when multiplied by the area and the percolation factor, gave the quantity of percolating water which reached the permanent ground-water level. The total annual precipitation on the outwash slopes is 62 000 acre-ft., of which 16%, or 9 800 acre-ft., is effective percolating water. Expressed as a continuous flow, the volume of percolating water amounts to 13.4 sec-ft.

Throughout the valley floor the surface of saturation is so close to the ground surface that capillary connection is maintained during most of the year, and percolation from precipitation is rapid. The depth of penetration is usually slight, however, because precipitation in single storms is small. Several storms in succession or a warm rain on snow will result in a rise of ground-water, but the total average ground-water supply from this source does not exceed 4 sec-ft.

Direct percolation from precipitation, therefore, furnishes a grand total of 44 annual sec-ft. to the underground supply of the basin.

TABLE 17.—PERCOLATION FROM PRECIPITATION UPON OUTWASH SLOPES OF THE INDEPENDENCE REGION.

(Mean seasonal values.)

TABOOSE GROUP OF PRECIPITATION GAUGES.

Contours bounding precipitation zones.	Area of zones, in square miles.	Depth of Precipitation, in Inches.		Volume of precipitation on zone, in acre-feet.	Percolation factor.	Quantity of Percolation.	
		On contours.	On zone.			Volume, in acre-feet.	Discharge, in second-feet.
Grass-4 500..........	28.07	6.0, 7.7	6.8	10 180	0.00	0	0
4 500-5 000..........	8.54	7.7, 9.0	8.4	3 830	0.10	380	0.5
5 000-5 500..........	8.14	9.0, 10.8	9.9	4 300	0.20	860	1.2
5 500-6 000..........	5.56	10.8, 12.9	11.8	3 500	0.35	1 220	1.7
6 000-6 500..........	3.42	12.9, 15.2	14.0	2 550	0.60	1 530	2.1
	53.73	....	....	24 360	....	3 990	5.5

OAK GROUP OF PRECIPITATION GAUGES.

Grass-4 500..........	24.57	4.8, 5.9	5.4	7 080	0	0	0
4 500-5 000..........	11.78	5.9, 7.3	6.6	4 150	0.05	210	0.3
5 000-5 500..........	9.23	7.3, 9.1	8.2	4 040	0.15	610	0.8
5 500-6 000..........	5.82	9.1, 11.3	10.2	3 170	0.30	950	1.3
6 000-6 500..........	4.82	11.3. 13.6	12.4	3 190	0.50	1 600	2.2
	56.22	....	....	21 630	....	3 370	4.6

BAIRS GROUP OF PRECIPITATION GAUGES.

Grass-4 500..........	19.56	3.3, 4.0	3.6	3 760	0	0	0
4 500-5 000..........	11.68	4.0, 5.2	4.6	2 860	0	0	0
5 000-5 500..........	9.76	5.2, 6.9	6.0	3 120	0.10	310	0.4
5 500-6 000..........	9.23	6.9, 8.6	7.8	3 840	0.25	960	1.3
6 000-6 500..........	5.11	8.6, 10.3	9.4	2 560	0.45	1 150	1.6
	55.34	....	....	16 140	....	2 420	3.3
Grand total.....	165.29	....	....	62 130	....	9 780	13.4

From Stream Channels.—The most important source of underground water in a desert region is percolation from stream channels. This process is continuous from perennial streams, although it varies with the discharge of the streams and the temperature, as previously indicated. Beneath each stream channel as it crosses the outwash slope is a "ridge" of ground-water rising from the general plane of satura-

tion. The inclination of the slopes of this ridge and the breadth of its base vary periodically with the stage of the creek and the time of year. There is complete saturation within its slopes and a movement of gravity water toward the general ground-water surface. A considerable quantity of water also percolates from intermittent streams.

Percolation from stream channels in the Independence Basin is confined to the creeks draining mountain canyons. There are 17 of of these streams, 11 of which are perennial throughout their channels, 5 are perennial over the upper portion of their channels only, and 1 (Dry Canyon) is entirely an underground stream. The surface flow of the two most northerly of these streams, Tinemaha and Red Mountain Creeks, discharges northward across the Poverty Hills into the Bishop-Big Pine region, but the percolation from their channels is tributary to the Independence Basin. The channels of streams entirely within the basin are continuous from their canyons to the U. S. Geological Survey gauging stations, below which they divide, irrigation ditches carrying all the flow except during the high-water period of wet years, when the excess passes down the natural channels. The problem is thus divided into the determination of percolation above and below the Government gauging stations. The first subject has already been discussed at length and need not be considered here in detail. An inspection of Tables 4 and 5 shows that for the creeks from Taboose to Hogback, inclusive, the total 21-year average discharge at the mouths of the canyons is 130 sec-ft. and at the Government gauging stations 84 sec-ft. If the flow of 2 sec-ft. from Spring No. 2 on Division Creek is included with the canyon discharge, the percolation loss above the Government gauging stations is 48 annual sec-ft. To this should be added 6 sec-ft., as indicated by the diagrams, for Tinemaha and Red Mountain Creeks, making a total of 54 sec-ft.

The quantity lost below these stations is not so easily determined, on account of the numerous channels and irregular flow. Estimates were made on each creek, based on the length of main channel and distributing ditches outside of irrigated areas. The loss per mile was assumed to be the average annual loss per mile for the upper channel of the creek, and the total percolation loss from stream channels below the Government stations was estimated at 25 sec-ft. of continuous flow. This estimate does not include percolation from waste irrigation water or surplus creek water which has passed east of the ranches.

The grand total addition to the underground supply derived by percolation from stream channels, therefore, is 79 annual sec-ft.

From Irrigation.—Irrigation has been practised throughout this region, in connection with farming, for at least 30 years, and is a permanent factor in the underground water problem. The total area under systematic irrigation is approximately 3 000 acres, divided into a number of isolated ranch groups which depend on the mountain creeks for their supply. Oak Creek, the largest of these streams, supplies about 45% of the whole area. The remaining area is divided among eight creeks and the Stevens ditch, which during the period of observation has been largely supplied by the surplus flow of the creeks. The acreage irrigated from each source is given in Table 18. About 50% of this land was originally desert, lying along the lower margin of the outwash slope, and is very porous. The remainder lies in the valley floor, where permanent ground-water is within reach of plant roots and where clay soils predominate. The location of the several areas is shown on Plate V. Alfalfa and grain are irrigated by

TABLE 18.—ESTIMATED NET VOLUME OF WATER USED FOR IRRIGATION IN THE INDEPENDENCE REGION DURING 1909.

Source of supply.	Area irrigated, in acres. *	Duty of water per acre for season, acre-feet. †	Total Volume of Water Used.	
			Acre-feet.	Second-feet for 6 months.
Taboose Creek	(170)	(12)	2 040	5.6
Goodale Creek	(110)	(16)	1 760	4.9
Division Creek	(80)	(16)	1 280	3.5
Sawmill Creek	(90)	(16)	1 440	4.0
Oak Creek, ranch No. 1	109	7.22	790	2.2
Oak Creek, ranch No. 2	49	15.40	758	2.1
Oak Creek, ranch No. 3	155	2.80	435	1.2
Oak Creek, ranch No. 4	260	2.34	609	1.7
Oak Creek, ranch No. 5	38	16.40	623	1.7
Oak Creek	(80)	(16)	1 280	3.5
Oak Creek	(100)	(5)	500	1.4
Oak Creek	(560)	(3)	1 680	4.6
Little Pine Creek	(300)	(14)	4 200	11.6
Symmes Creek	(160)	(5)	800	2.2
Shepard Creek	(280)	(12)	3 360	9.3
George Creek	(160)	(12)	1 920	5.3
Stevens ditch	(310)	(8)	2 480	6.9
	3 011	....	25 955	71.7

* Areas in parentheses obtained from approximate field observations; other areas obtained by careful field measurement.

† Figures in parentheses assumed from observations on Oak Creek ranches.

flooding, and corn by the furrow method. Three crops of alfalfa are raised each year, and the irrigating season extends from about April 15th to October 15th, although some farmers irrigate 9 months in the year. Grain is irrigated early in the season, and corn late, so that the water is continually used. In most places the use of water is lavish, and no attempt is made to economize it or even to apply the quantity best suited to the crop and soil conditions.

A basis for determining the percolation from irrigation is a knowledge of the duty of water, or the quantity of water used in maturing a given area of crop. This was obtained in 1909 by carefully measuring the quantity of water used daily during the irrigating season on five typical ranches which derived their supply from Oak Creek. On ranches where there was a continual waste from irrigation the surplus water was also measured. Areas in crop were obtained from a careful stadia survey of each ranch.

With conditions on these typical ranches in mind, an examination was made of all other ranches in the region, and values were estimated for the duty of water on each. The number of acres irrigated and in crop was also determined approximately by reference to subdivisions of the public survey. From these data the volume of water used for irrigation was determined, as shown in Table 18. The total volume used during the 6 months, April 15th to October 15th, is about 26 000 acre-ft., equivalent to a continuous flow of 72 sec-ft. during the period. When spread out over 3 010 acres, this represents an average depth of 8.6 ft. This result probably represents an average practice throughout the Owens Valley, for the duty of water measured by the Reclamation Service during the season of 1904 on two typical ranches near Bishop was 7.11 and 9.17 acre-ft. per acre.

The distribution of this water, as regards evaporation, transpiration, and percolation beyond the reach of plant roots, is the next step in computing the ground-water supply from this source. Direct evaporation is relatively small, for the water when spread out over the fields is shaded by the crop and sinks rapidly into the ground. Probably 10% would cover this loss. The transpiration loss from alfalfa during the irrigation season has already been computed as 3.43 ft. depth of equivalent water, or 40% of the average volume of water applied to crops. The transpiration loss from corn and small grains is probably less in this locality, but the direct evaporation loss is greater. There-

fore 50%, or 4.3 ft. depth, represents the quantity of water applied in irrigation in this region which is absorbed by the atmosphere. The other 50% is a permanent addition to the ground-water supply, and is equivalent to a continuous flow of 18 sec-ft. throughout the year.

From Flood Water.—The quantity of percolation from surplus creek water, which spreads out over the valley floor to a greater or less extent, is difficult to determine. Of the 84 sec-ft. average flow at Government gauging stations, 61 sec-ft. are disposed of in channel percolation and irrigation. Possibly 5 sec-ft. of the remainder reach Owens River. This leaves 18 sec-ft. to be divided between evaporation and percolation in the flats between the ranches and the river. The area flooded averages about 5 sq. miles during June and July. The loss by evaporation during this period from a shallow pan in soil was about 24.5 in., and, as the conditions are similar, this represents approximately the loss from shallow flood water. The volume expressed as a continuous flow for two months is 55 sec-ft., or, for a year, 9 sec-ft. The other 9 sec-ft. can be assumed to represent the percolation from this flood water. It is not a permanent addition to the ground-water supply, however, for the surface of saturation is only a few feet below the ground surface in this area, and evaporation from damp soil and transpiration from natural vegetation soon reduce the ground-water surface to its normal position.

Summary of Percolation.—The four sources of ground-water are percolation from direct precipitation, from stream flow, from irrigation, and from flood water in the valley floor.

The first of these yields about 44 annual sec-ft., of which 61% is from the intermediate mountain slopes, 30% from the outwash slopes, and 9% from the valley floor. Percolation from streams yields about 79 annual sec-ft., of which 68% is above Government gauging stations and 32% below. Irrigation yields 18 annual sec-ft. and flood waters in the valley floor 9 annual sec-ft.

The grand total ground-water, therefore, is 150 annual sec-ft., of which probably 75% reaches the deeper strata of the valley fill. The rate of recharge of the basin, as thus determined, differs by less than 4% from the ground-water loss previously computed. The reliability of the data is thus confirmed as well as the correctness of the assumptions.

Safe Yield.

Thus far, this paper has presented conditions as they are found to exist in a natural state. The problems which the engineer has to solve are those connected with the artificial extraction of water from underground reservoirs. First among these is the determination of the safe annual yield or the limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve. A second problem which naturally accompanies the first is the devising of methods for increasing artificially the safe annual yield of reservoirs which are apparently already developed to the limit. The writer will outline his ideas, in the hope that they will suggest a constructive line of discussion which will lead to a better understanding of these subjects.

It is obvious that water permanently extracted from an underground reservoir, by wells or other means, reduces by an equal quantity the volume of water passing from the basin by way of natural channels. This is illustrated by the commonly recognized fact of the drying up of springs and cienagas as the result of heavy pumping. The theoretical limit for safe draft, exclusive of return water, therefore, is the average rate of recharge for a basin. The practical limit, however, depends on the relation of draft to storage capacity, within economic pumping limits. Where the storage capacity is very large as compared with annual draft, the theoretical and practical limits should nearly agree, as the storage reserve can be drawn on in periods of protracted drought. For basins with comparatively small storage capacity, the practical limit will be less than the theoretical. Draft computations may be made with the mass-diagram as ordinarily used in surface storage problems. Storage capacity is determined from the area of water-bearing material, limiting depth for economic pumping, and percentage of voids capable of depletion. The supply is the quantity of water annually absorbed by the porous material of the basin. This may be determined each year by methods similar to those used in the Owens Valley studies.

The draft thus obtained, however, is not the safe yield of the basin, for there are always certain residual losses which cannot be entirely prevented, such for instance as soil evaporation from cienaga lands. These residual losses must be ascertained and deducted from the gross draft. The quantity thus obtained may be persistently with-

drawn from the basin without causing general depression of the water plane to the point where pumping operations must cease for economic reasons.

The determination of residual losses presents difficult problems. Some of the conditions which are responsible for these losses are the following:

1.—The elevation of the impervious rim at the outlet being less than the elevation of the water plane in the lowest depression of the basin, thus allowing ground-water to escape as underflow. The quantity of water thus dissipated depends on the transmission capacity and area of the porous material overlying the rim and the available head. In most cases the volume of water thus lost is relatively very small.

2.—The outlet of springs being at a considerably lower elevation than the general water plane of the basin in the outlet region. Such a condition may exist where an arroya has cut a channel through the impervious rim at a point where the surface falls away rapidly down stream. Such losses are also relatively small.

3.—The occurence of water under Artesian pressure in underlying strata of porous material confined between more impervious layers of fine sand or clay. This is the least recognized, but yet the most important, cause of residual ground-water loss. The effect of Artesian pressure is to force moisture through pores or fractures in the impervious capping and thus maintain a permanent ground-water plane near the surface. The water continually supplied from below is disposed of either by evaporation from the soil surface and vegetation or by escaping at the surface in springs or seepages. These losses persist as long as the Artesian pressure is sufficient to force the water through the overlying strata. The volume of these losses during any period of one or more years bears a functional relation to the average Artesian pressure during the same period. The writer states these conclusions as the result of a careful study of records and conditions in a number of differently situated Artesian basins.

These conclusions are well illustrated by the following facts of common knowledge. First, consider the result of abnormally large precipitation for a period of one or more seasons. The ground-water accretions exceed the losses from the basin, the excess water accumulates in the voids of the porous gravels surrounding the confined strata,

and the free ground-water surface rises throughout the basin. Within the area of confined gravels hydrostatic or Artesian pressure increases. A greater quantity of water is forced through the overlying strata, not only over the area already moist, but from a circumscribing zone within which the pressure was previously insufficient to maintain a shallow ground-water surface. The observed result, therefore, is increased spring and seepage flow and an enlarged area of moist cienaga land from which evaporation occurs. Second, assume a series of dry years. Ground-water storage is depleted, the free ground-water plane falls, Artesian pressure decreases, and less water is forced through the overlying strata. The observed result is decreased spring and seepage flow and shrunken evaporating area. The latter occurs, because, for the new conditions, the rate of evaporation from the outer zone of moist soil exceeds the rate of supply from below. The accumulation of water in the soil is drawn on, lowering the water level to the limit of capillary action. A similar result occurs where relief is afforded to Artesian pressure by the drilling of many deep wells drawing from Artesian strata. In some of the Southern California Artesian basins, which formerly possessed cienaga lands, relief of Artesian pressure by wells and heavy pumping has dried up such lands.

The importance of residual losses, due to Artesian pressure, is forcibly shown by the Owens Valley studies, where it was found that in a natural state 81% of the total yield of the Independence Basin was lost by evaporation from soil and vegetation. Similar conditions, in a slightly less degree, existed in many of the Southern California basins before ground-water development was undertaken. The increased pumping of the last 10 or 15 years has eliminated evaporation losses almost entirely in some of the smaller basins. In the larger basins, such as the San Bernardino Valley and Coastal Plain, the reduction has not been as great, having ranged from 30 to 50% of original evaporation losses in the various basins. In these basins evaporation losses formerly represented from 50 to 75% of the total ground-water supply. Hence, the residual evaporation losses to-day represent from 15 to 35% of the total ground-water supply for the large Southern California basins, and can be said to average 25 per cent.

The quantitative determination of the residual losses from an underground reservoir can only be made after a detailed study of the local

conditions. The factors to be considered are the topography and geology of the basin and its porous filling, the distribution and type of sources of percolating water, the rate of evaporation and transpiration, the depth of capillary action and the character of the soil within the evaporating area, the necessity for irrigation and the value of overlying lands for agricultural crops, the present or probable ultimate method of development of water, and the present or probable future use. The general condition favorable for small residual losses is the possibility of eliminating the evaporating area by lowering the water plane below the reach of capillary action. This may be done by the relief of Artesian pressure, by shallow pumping within the evaporating area, or by drainage. The first of these methods would result in reduced pressures in existing wells in the Artesian area and possibly lowered water levels in the back-water zone, especially if the ground surface has a steep slope. Shallow pumping and drainage, on the other hand, may be physically impractical or prohibitive in cost. Their success depends largely on the existence of shallow water-bearing strata from which water can be readily drawn.

There are three cases which arise in the determination of residual losses: first, a basin already fully developed or suffering from overdraft; second, a basin where the supply is partly developed; third, a basin entirely undeveloped. The first case can be recognized by inspection of the present or former evaporating area in connection with local confirmatory evidence and past records of water levels, yield of wells, etc. The residual losses may be ascertained from observations and measurements of existing conditions. The second and third cases require assumptions as to the method or combination of methods by which residual losses will be reduced to a minimum. These assumptions should be made after a careful study of local physical conditions and the probable future use of the water. The next step is the determination of existing evaporation losses, by contouring the ground surface and water plane, and ascertaining the soil evaporation losses for various depths to ground-water. The final step, namely, the determination of the percentage by which existing losses will be reduced by future development, is as yet largely a matter of judgment. Having arrived at some definite value, however, the residual losses due to evaporation can be computed, and, when combined with the losses from underflow or deep springs, the total quantitative result is obtained.

The thorough investigation of residual losses is essential in any determination of safe yield, and for this reason the writer has discussed the subject in detail.

Passing now from the determination of safe yield as limited by existing conditions to a discussion of methods for increasing safe yield artificially: Obviously, to accomplish the latter, either the rate of recharge of the basin must be increased or the percentage of unused water escaping from the basin must be decreased. Practical methods which suggest themselves are:

(1) Reduction of residual losses to the lowest possible quantity;
(2) Elimination of needless waste of underground water; and
(3) Increased absorption of surface flood waters.

The subject of residual losses has already been discussed at length. The writer wishes to emphasize the fact, however, that a basin has not been fully developed as long as the evaporating area persists in years of drought. The evaporating area is fully as important a criterion of the relation of withdrawals to supply as the water plane. A falling water plane does not of itself indicate overdraft. It is only when a rapid shrinkage and disappearance of the evaporating area accompanies a falling water plane that dangerous overdraft is indicated. Hence, in a closed Artesian basin from which the evaporation area has not disappeared, a greater yield may be obtained, provided an intelligent plan of development is followed.

A very common source of needless waste is from Artesian wells which are allowed to flow when the water is not in use. The wastefulness of this practice is so evident that it need not be discussed in this paper. Its continuance is made possible by lack of recognition of the ultimate effect of the practice among the owners of such wells. The writer feels that it is every engineer's duty and privilege to assist in guiding aright public opinion in matters of common interest, and suggests the subject of conservation of Artesian water as being pertinent in many communities.

The practicability of increasing the ground-water supply by bringing about greater absorption of flood water has been demonstrated in a number of California basins. The most extensive work of this kind is probably that done on the alluvial cone of Santa Ana River in the San Bernardino Valley. The method there used is to divert the flood

water of Santa Ana River in contour ditches from which it is distributed into smaller ditches which in turn subdivide, until finally the water spreads out over the porous alluvial gravels in a thin sheet and is absorbed. During the past few years the volume of water thus stored has averaged 12 000 acre-ft. annually, costing about 15 cents per acre-ft., including interest on the cost of permanent works. The work is capable of further expansion. The ultimate limit will be the ability to handle the violent floods, which are of frequent occurrence. The problem is not that alone of controlling the water, but of disposing of silt. The water is normally clear and is free from silt soon after the flood crest passes. Flood water, however, carries great quantities of silt, which deposits as soon as the velocity is checked. This forms an impervious layer of slime which seals the gravels and must be broken up and eventually removed in order to use the same spreading ground continuously.

The conditions on most California streams tributary to closed basins correspond to the Santa Ana. The writer is of the opinion that complete absorption of even ordinary floods on these streams cannot be brought about without temporary surface storage. This must be accomplished either by utilizing storage sites in the stream channel or by construction of contour levees on the alluvial cone. The purpose of such reservoirs would be to act both as settling basins and as temporary storage sites. From these reservoirs the clear water would be released and brought into contact with the absorbent gravels by any method which proved most efficient under the local conditions.

In conclusion it may be said, first, that the rate of recharge of underground reservoirs of the closed-basin type is a definite quantity capable of measurement with a fair degree of accuracy; second, that safe yield is a quantity less than the rate of recharge, its quantity depending on the available storage reserve of the basin and residual ground-water losses; third, that under certain circumstances it is possible to increase the safe yield of a fully developed basin.

DISCUSSION

JAMES OWEN,* M. AM. SOC. C. E.—Although Mr. Lee's paper is confined somewhat to underground water supplies in the western part of the United States, a great deal of investigation has been done and a great deal of money has been spent and wasted on such supplies in the eastern sections and in localities near New York City, and it seems that, if it were possible in the future to define certain rules and principles governing the question of getting water from the ground, it would be better for everybody. Mr. Owen.

The section around New York has a variety of topographical and geological conditions. According to the speaker's idea, the underground supplies can be defined under about four heads, that is, the original sandstone deposition, prior to the volcanic upheaval; the volcanic upheaval of gneiss in Westchester County and New York, and the trap in New Jersey; the glacial and post-glacial depositions, and, incidental to these, the terminal moraines; and finally, in lower New Jersey, what might be called the post-tertiary deposition. The first and the last, the original sedimentary deposition of the sandstone and the post-tertiary deposition, have fairly well-defined radii of supply.

It is well known that water can usually be obtained by driving through sandstone. In New Jersey, if one drives through certain strata, water can be obtained, and an interesting incident was shown when Asbury Park, N. J., desired a water supply and was advised by Professor Gay, State Geologist of New Jersey 30 years ago, to go down 800 ft., at which depth all the necessary water could be obtained. On trial, water was found within 40 ft. The final result has been that all through that shore territory the supply of water has been ample, good, and economical. In this section, however, the main consumption has only lasted about 4 months in the year, and during the other 8 months, the disposal of the underground supply would have failed to be profitable for steady communities.

In the sandstone formation, a good and reliable supply can always be obtained, subject to the chemical and natural properties of the water. In New Jersey, wells have been sunk 400 or 500 ft. below tidewater and ample water has been found, but its chemical constituents have made it rather detrimental for public use. In one case, where the well was put down 400 ft., the deposition of lime was about 8 in. in 4 months. That, of course, debarred its use for public purposes. The water, however, was storage water, and the slow percolation through the sandstone had not allowed for a free flow; consequently, the chemical deposition ensued.

* Newark, N. J.

Mr. Owen. In the other two regions, the volcanic and the post-glacial formations, there is a certain amount of uncertainty in regard to the supply. In the volcanic formation with a slight cover, of course, there is no water unless one goes into the rock; and in either the trap, gneiss, or Atlantic formation, the supply is uncertain, erratic, and unreliable, and very rarely successful.

In the post-glacial formation, the drifts fill up the subterranean canals, as they may be called, and the terminal moraine depositions. In this case the water supply is fairly reliable within certain limits. In the speaker's experience there have been two or three curious propositions relating to this question. A certain city put in a water plant in a post-glacial deposition. When the wells were put down they overflowed. Pipes were driven down 80 or 100 ft., and left up in the air 10 or 15 ft., and still the wells overflowed. The pumping plant was started, and, of course, the overflow was gradually lowered. Incidental to that was the fact that, a little above the pumping plant, a man owned a very heavy spring which was totally stopped after a short period of pumping. He brought suit against the company, and, by a curious coincidence, the pumping plant broke down at a certain hour on a certain day, and a certain number of hours afterward, the spring ran afresh. That incident showed the underground capacity of that subterranean gulch, including the capacity of the underground storage.

That formation was almost all sand and gravel. The water-table in 3 years of pumping was lowered from an overflow of 6 or 8 ft. above ground to a ground-water flow of 22 ft. below the surface, showing that the company was pumping beyond the capacity of the delivery or the water flow of the country.

Take the other case, where there is a till flow, that is, in the glacial deposit termed the till, where the percolation is very slow. In certain cases under the speaker's care, the flow of the wells after a rainstorm was carefully timed, and the percolation, instead of being immediate, took about 2 days. In the case of one large well, where six or seven holes had been bored into the limestone, and where it was important to have supply enough for the examination, careful note was taken of the times when there was enough water and when the supply was deficient. Examination showed that, after a heavy rainstorm, it took 2 days for this flow through the till, that is, the drift deposit, to get through the rock and into the wells. This shows the extremely slow rate of percolation.

There are a great many interesting questions in the whole region about New York, and it is especially necessary to have known facts tabulated, as there has been a great deal of money wasted, especially in developing what is known as a mysterious underground supply.

In the case previously cited, the wells were put in for the city under the direction of a competent engineer, and the speaker remarked at the time that he was surprised at his being brave enough to put in such a plant for that community. The result has been that that city has been compelled to buy up land and territory after territory to provide a sufficient underground supply. Mr. Owen.

G. E. P. SMITH,* M. AM. SOC. C. E. (by letter).—The publication of this scholarly paper on investigations in the Owens Valley, and the studies and conclusions based thereon, must be welcomed by all hydraulic engineers of the arid West. In addition to its immediate or local value, the paper affords a clear and concise exposition of the general principles of ground-water storage, of recharge and loss, and of the extent to which ground-waters can be drawn on for municipal water supplies, irrigation, or other purposes. So far as the writer knows, it is the first comprehensive work of its kind, and the author has the distinction of being a true pioneer of the Profession. The paper itself marks a new era in the development of ground-water studies, an era in which scientific basis and logical methods supersede much idle speculation and many misconceptions. Mr. Smith.

Too much credit cannot be given to Mr. Lee for the thoroughness and application of system displayed in his investigations. These features are exemplified in the excellent analyses of rainfall distribution, of seepage losses, and of soil evaporation tests. Where arbitrary factors have been necessitated, they have been based on painstaking inspections and on rare good judgment. In such cases, also, the author was assisted by the extreme uniformity of natural conditions in the Owens Valley, especially of topography, valley fill, soil and vegetation. The application of system in the investigational work is reflected in its orderly presentation, and in the use of graphical methods, features which add greatly to the value of the paper.

The writer's purpose is not to criticize, but to broaden the foundation on which the deductions and generalizations of the paper are based, and to assist in the extension of their application to a wider range of climatic and geologic conditions.

Beginning in 1906, the Arizona Agricultural Experiment Station has carried on ground-water investigations under the writer's charge in several valleys of southern Arizona. These valleys vary greatly in the degree of aridity, from the grassy sub-arid Sulphur Spring Valley, which is comparable to Owens Valley, to the severely arid Lower Gila Valley. The chief determining factor is the altitude. The ground-water hydrology is exceedingly diverse in character, so that it is difficult to frame generalizations that are applicable to all the valleys.

---

* Tucson, Ariz.

Mr. Smith. The most detailed study has been that of the valley of the Rillito,* a tributary of the Santa Cruz, as shown in Fig. 13. There are striking similarities between it and Owens Valley. Both are desert valleys in which the surrounding drainage is toward a broad, flat area, or playa, and therefore they come within the meaning of the term "bolson" or "semi-bolson", as defined by Tolman.† The Pantano watershed spills its surplus water to the Rillito; the Rillito delivers a portion of its drainage to the Santa Cruz, and the Santa Cruz, on rare occasions, has a continuous discharge to the Gila River. Excluding the Pantano bolson with its 620 sq. miles, the total drainage area of the Rillito is 327 sq. miles, of which 56% is mountainous (granitic), 30% consists of dissected gravelly outwash slopes, and 14% is valley land. The area is nearly equal to that of the Independence Region, though the percentage of mountain area is higher. The lengths of the valleys are the same—25 miles—and both derive practically all their drainage from the right-hand side. The mountain rainfall, also, is equal in the two cases, varying from 10 or 12 in. in the foot-hills to 30 or 35 in. at the crests.

The distinctions are: the Rillito Valley lies at an elevation of about 2 400 ft.—considerably lower than Owens Valley—and consequently the temperature is higher and evaporation is greater; the mountainous area drained by the Rillito is on the windward side, and hence the rainfall is comparatively high for the region; the rainfall-altitude curve shows a continuous rise to the summit, at 9 000 ft.; and there is no perennial grass area, but, instead, the high mountains are forested with pine, and the lower slopes and valley floor are covered with a diversified desert vegetation, with mesophytic trees along the stream courses.

A survey of the water-table has shown that the river channel is not coincident with the ground-water trough; the ground-water on the south or left side has a component movement away from the river, especially during and after floods. The movement has been studied in lines of wells at right angles to the river, and the recharge which occurs during a flood season has been shown to progress away from the river as a true wave.‡ At no point has the water plane shown any response to direct precipitation, the rainfall penetrates only a few feet into the soil in the most favorable years, and it appears

* *Bulletin* No. 64, Arizona Agricultural Experiment Station, 1910.

† He states: "I therefore suggest that the word be used to cover the watershed of a centripetal drainage system, including all the area within the limits of the divides. The bolson may depart somewhat from a perfect topographical basin, for evaporation on a slope may prevent the development of a through drainage, and foster the centripetal variety. Those bolsons whose surface water in times of flood reaches some river thoroughfare some lower bolson, or the ocean direct, and consequently the playa portion * * * is poorly developed or lacking, may be called semi-bolsons."—*Journal of Geology*, XVII, No 2, p. 141, February-March. 1909.

‡ *Bulletin* No. 64, Arizona Agricultural Experiment Station, p. 184.

Mr. Smith.

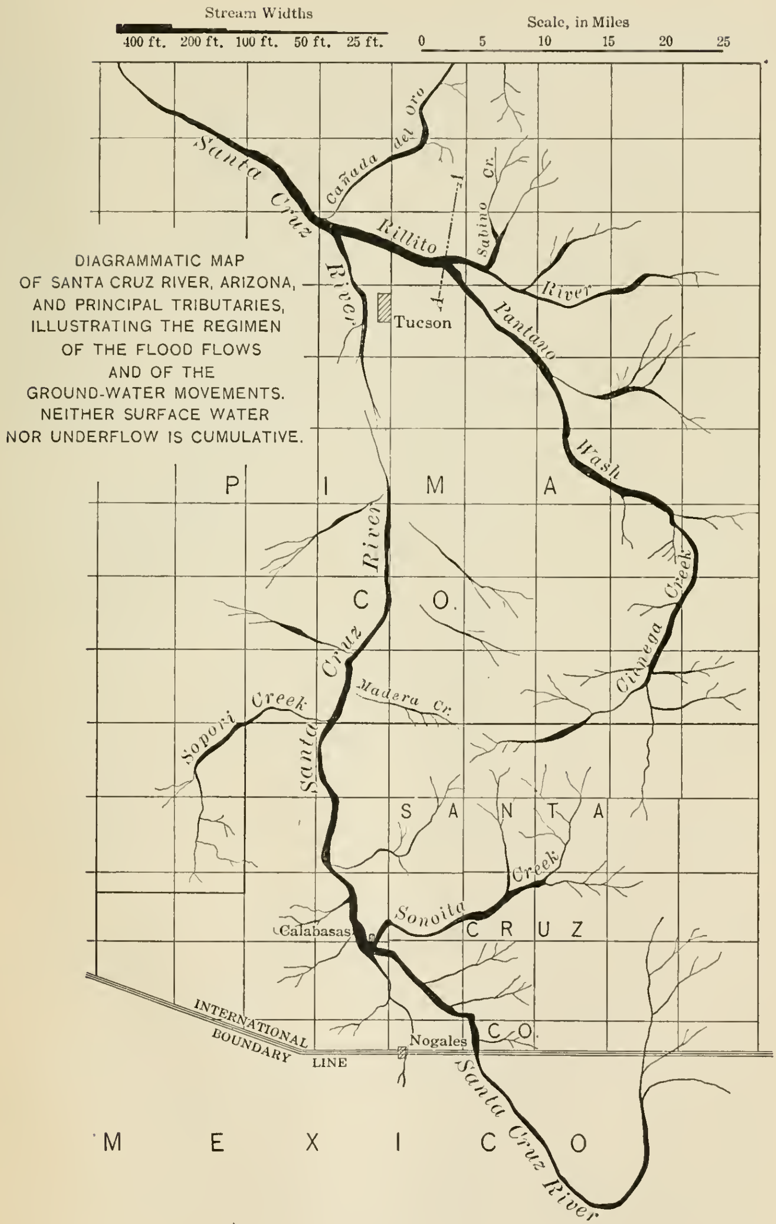


FIG. 13.

Mr. Smith. that the recharge is due solely to the seepage of the river flows into the porous gravels.

The structure of the valley is of fundamental importance. Fig. 14 is a section along the line, *AA*, the location of which is shown in Fig. 13. The section includes the mountain face, the Rillito Valley, and the smooth slope which separates the latter from the Santa Cruz Valley. The valley fill includes deposits of three distinct periods. Uppermost are the Recent deposits along the stream courses, laid down by the present system of rivers. The main body of the fill, however, is the Catalina Mountain outwash, probably Pleistocene; and, underlying this are older deposits, exposed in small outcrops in the foot-hills. The Recent deposits include loose, coarse, water-bearing gravels; the gravels of the outwash are for the most part tightly cemented with a secondary calcareous deposition which, when present in great quantity, is called caliche. As a rule, the wells in the outwash yield poor supplies. Thus the Esmond Well, in the center of the valley, southeast of Tucson, which was drilled to a depth of 1 480 ft., has only 3 ft. of water-bearing gravel, the rest of the formation being alternating strata of cemented gravel and clay. Many wells in the outwash yield practically nothing, while others, more fortunately situated with reference to old stream beds, yield small supplies of from 50 to 250 gal. per min. The fact that the first water-bearing stratum in the Recent fill yields good supplies has led to the general adoption of caisson well curbs built of reinforced concrete, for wells situated within the area of Recent fill.

The interchange of water between the Recent fill and the outwash is difficult to estimate, but, in the aggregate, it must be quite extensive. The author remarks on page 151:

"Along the coast of California, shales and cemented gravels predominate, and are practically non-water-bearing in comparison with the porous gravels filling the basins."

Hence, there arises an ambiguity with regard to what shall constitute the basin—the porous gravels only, or all the fill within a rock trough. The author has used the latter construction in his work in Owens Valley. It is not likely that close estimates can be made for the porous younger deposits alone. Referring to *Bulletin* No. 64 again, on page 189 is the following:

"It may be questioned whether the seepage loss, if measured at the present time will indicate correctly the available water supply for pumping. On the one hand, present data show a great leakage from the valley, either toward the south or downward into the older [Pleistocene] formation, and this leakage must continue in the future. On the other hand, the seepage loss of floods will be greater if the groundwater supply has been reduced by pumping; indeed, it is one of the important effects of pumping that the recharge of the ground-

Mr. Smith.

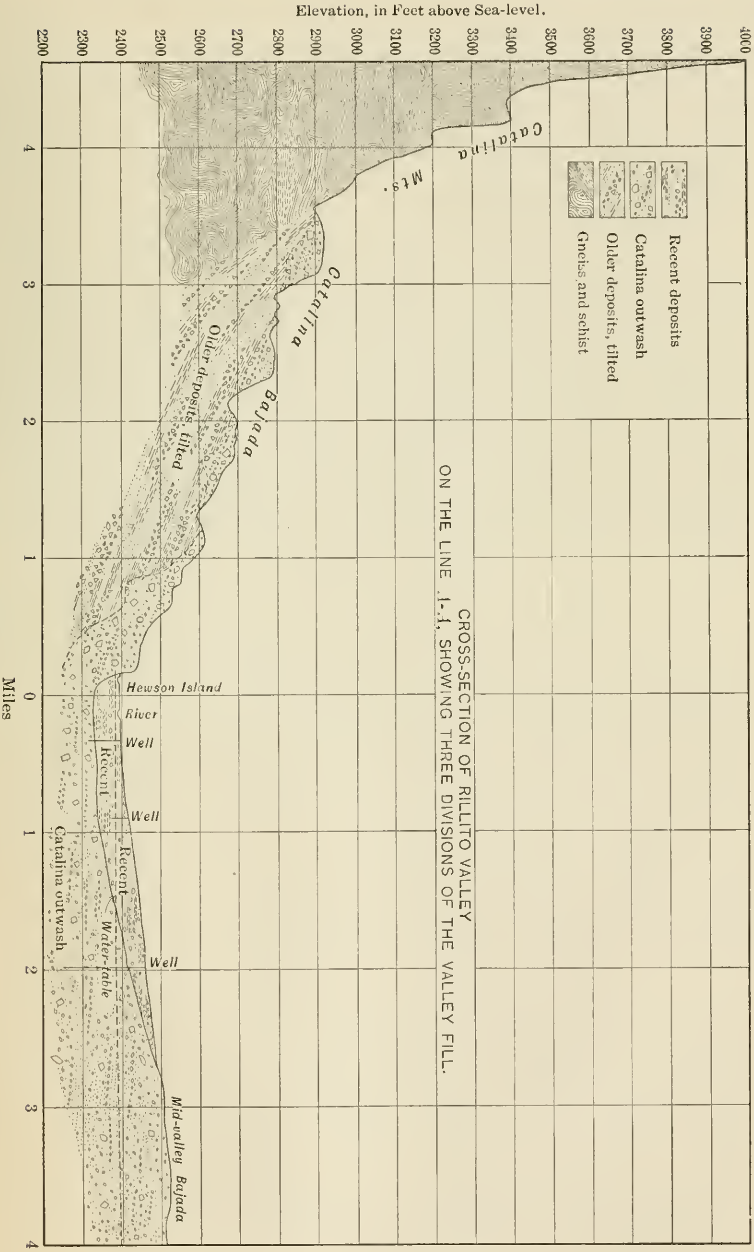


FIG. 14.

Mr. Smith. water will be thus increased. At present it may well be assumed that these two influences are balanced."

The cementation described above is a saving feature in arid regions, since it reduces the under-drainage and holds the ground-water at shallower depths. In the parallel valleys west of the Santa Cruz, the drainage capacity exceeds the annual recharge, with the result that the water-table lies at depths of from 200 to 800 ft., even along portions of the stream courses.

In estimating the annual recharge of the Rillito Valley, the writer made use of the measured run-off from Sabino Canyon, records for which were available, for the period, 1904-09. By a comparison of areas and altitudes, and of simultaneous gaugings at the mouths of canyons, the run-off for the other tributaries was estimated. Measurements of seepage loss were the next need. For moderate floods, the problem was, not the percentage of loss, it being total, but the quantity and location of the loss. Logs of wells revealed the extent of the storage capacity. With the foregoing data the recharge for a distance of 12 miles was estimated at 23 000 acre-ft. per year. It is hardly necessary to disavow any high degree of accuracy, but, even though the probable error is 20%, such estimates are highly useful.

Transpiration.

In the Owens Valley experiments, the evaporation from the soil and transpiration from the salt grass were treated together, and a straight-line relationship was established between the water loss and the depth of the water-table below the ground surface. It is worthy of note that the loss of ground-water from the salt grass in the 3-ft. zone was sufficient for the irrigation of an equally large area of alfalfa, and the loss, where the depth to water was 4 ft., was sufficient for the irrigation of most other crops.

If two additional tank sets had been provided, and maintained without grass, one with water level at a depth of 2 ft. and one with depth of 4 ft., and thus used as check tanks, it would have been possible to differentiate between the combined effect of evaporation and transpiration and the effect of evaporation alone. The evidence of the data presented indicates that the combined loss is approximately twice the loss due to evaporation from the soil. For it is to be noted from Fig. 10 that the loss-depth line in summer approaches closely to the summer loss from a free water surface, while in winter the loss-depth line falls short of the corresponding free-water loss about one-half. Although the estimated summer transpiration loss from alfalfa is 87% of the free-water loss, yet the transpiration from salt grass must be much less than that from alfalfa, because of the smaller leaf surface exposed, and the direct evaporation from the soil must be greater than in the case of alfalfa.

In southern Arizona and contiguous areas, the normal desert valley has no extensive flat shallow-water district like that of Owens Valley. The water plane is usually at a depth exceeding 15 ft., and is thus beyond the influence of capillary action. In some cases there are small cienegas, covering an acre, more or less, and in the Sulphur Spring and San Simon Valleys there are playas of considerable extent; but many valleys of this region have modified river drainage systems, with bottom-lands carrying a surprising quantity of vegetation, usually trees and shrubs. Mr. Smith.

Formerly, the river channels were poorly developed or entirely lacking, and the occasional floods spread out over the bottom-lands and supported a growth of sacaton and other grasses; but, with the coming of the white man, with his herds of cattle, and the overstocking of the ranges in the Eighties, great areas were denuded of grass, and the concentrated flood-waters soon cut wide channels through the loam and adobe down to a gravelly bottom. Following the change in the character of the run-off, the sacaton disappeared, and trees, notably mesquite, took possession. Where the depth to ground-water is within 25 or 30 ft., the trees have become continuous forests covering the ground. That the trees send their roots down to the water-table is easily proven, for the caving banks of rivers and arroyas reveal them. The mesquite, in particular, has deep, strong, tap-roots, with a generous development of feeders.

The hypothesis has been held by the writer for a long time that the water drawn up through trees and transpired constitutes the principal loss from the ground-water reservoir, and that, in some cases, this loss is the total loss, while in all cases evaporation is an agency of less import. This paper tends to confirm the hypothesis. The author states, however, concerning the processes of soil evaporation, transpiration, and stream flow, that "with the exception of transpiration from trees", they "are now capable of measurement with relative accuracy at reasonable cost." In order to apply the principles which he has so ably developed to the regions somewhat more arid than Owens Valley, it is essential to learn much more than is now known about tree transpiration.

Botanical literature offers little assistance in this problem. The single experiment or estimate which is found in all botanical textbooks is that in Austria a high beechwood forest transpires 30 000 liters daily per hectare during the growing season of 6 months. This is equivalent to 22 in. depth of water over the land. It is stated, further, that from 250 to 500 grammes of water are transpired for every gramme of dry solid matter produced.

Mr. Lee says of transpiration that it "differs in different species of plants," and "King's experiments indicate that humidity does not affect transpiration. For a species growing in a definite locality, light

Mr. Smith. and available soil moisture are the controlling factors." These statements are surely open to question, as will be explained presently. It is probable that all plants tend toward the same rate of relative transpiration per unit of surface exposed, and the principle is well established that humidity is a potent factor of transpiration, as well as are light and soil moisture. The significance of these corrections lies in the fact that ground-water reservoirs are of chief importance in arid regions; and in such regions, with low humidity, brilliant light, and high rates of transpiration, even the xerophytic, or drouth-resistant, plants, under certain conditions, become most profligate in dissipating the only available water resources.

Recent researches of the Desert Botanical Laboratory of the Carnegie Institution have brought out some pertinent new principles of transpiration. The work of F. Shreve in the tropical mountain rain-forest of Jamaica has yielded the conclusions that humidity is a factor of much influence, and that transpiration is approximately proportional to evaporation. He says:*

"Although high humidities (90 to 95 per cent.) have been found to reduce the absolute rate of transpiration below its amount at relatively low humidities (55 to 71 per cent.), as is to be expected, the rate of relative transpiration continued to be of the same general order of magnitude at all humidities which are well above the minimal point for rain-forest plants."

Relative transpiration is a term used to define the ratio of transpiration to evaporation. Further, Shreve has studied data obtained by him in Jamaica in comparison with similar investigations carried on at Tucson, by B. E. Livingston on several desert ephemerals, and by Edith B. Shreve with the palo verde, *Parkinsonia,* which is rated as "a most successful desert tree". To quote again:†

"A general review of the data under comparison indicates that, in spite of minor differences, there is a greater uniformity among the relative transpiration maxima for the rain-forest and for the desert than might be expected. When such a uniformity is considered in the light of the fact that the evaporation is very many times greater in the Arizona desert than in the Jamaican rain-forest, it forces the conclusion that the transpiration-rates in the plants of the two regions must be roughly proportional to the evaporation-rates, else the relative transpiration-rates would not remain so nearly equal. In short, it is the desert plants in which the rate of transpiration is high and the rain-forest plants in which it is low, which is quite the reverse of the commonly accepted view."

G. F. Freeman, plant breeder of the Arizona Agricultural Experiment Station, has made simultaneous tests of transpiration on a peach tree and a creosote bush growing in close proximity. He found a very

* "Year Book No. 12," Carnegie Institution of Washington, 1913, p. 74.

† *Ibid.*, pp. 75-76.

slightly higher transpiration-rate for the peach tree per pound of green matter, but, when based on the area of leaf surface, the rate for the creosote bush was in excess.* The creosote bush is an extremely xerophytic plant, and forms the principal vegetation of the dryest slopes. Mr. Smith.

The establishment of the principle of equal relative transpiration-rates makes it possible to eliminate from many discussions factors such as light, air pressure, temperature, and humidity, and to base estimates of transpiration on the more easily measured evaporation from a free water surface. Also, the principle harmonizes the author's estimate of annual transpiration loss from alfalfa with King's estimate for clover in Wisconsin. The leaf characteristics of the two crops are very similar. The estimate for alfalfa is 41 in. depth of water transpired through the plants and 10 in. additional evaporated from the soil; for clover the estimate is 22.3 in. for both processes combined. The rates of evaporation in Owens Valley and in Wisconsin, however, are approximately as 2 to 1.† Since the rates for southern Arizona and for Wisconsin are as 2½ to 1, the inference can be drawn that in Arizona it requires about 56 in. for the proper irrigation of alfalfa.

Before condemning all desert vegetation indiscriminately, however, an ameliorating factor must be taken into consideration. Desert plants possess many queer habits by which they protect themselves from the tendency toward high transpiration-rates. On hot dry days they close their stomatal openings. In times of drouth they drop their leaves. The leaves are invariably small. The leaves of many species are covered with hairs. Some of the cacti are provided with water storage organs either in the roots or in the stems. Hence, plants pass successfully through seasons when the soil moisture around their roots becomes as low as 4 per cent. This power of self-protection is vital to the vegetation of the outwash slopes (usually but improperly called mesas), where the depth to the water level ranges sometimes as great as 600 ft. There is no evidence, however, that the power is exercised by trees growing on the bottom-lands, where the roots are bountifully supplied from below the ground-water table, or by alfalfa and other field crops, so long as they are well irrigated.

Adopting now the principle that transpiration varies as evaporation, soil moisture conditions being assumed to be uniform, the transpiration-rate for the beechwood forest previously quoted must be multiplied by 2½ to obtain the rate for arid regions. The result is 55 in. depth of water per annum, a quantity that probably represents fairly well the transpiration loss from the cottonwood trees which fringe the rivers for miles and are abundant usually on the upper courses of the tributaries. The loss from mesquite forest, on account of the

* Unpublished work.

† See new Evaporation Chart, "The Plant World," Vol. XIV, No. 9, 1911, p. 219.

Mr. Smith. smaller leaf expanse, is perhaps one-half as great as that from cottonwood trees.

As a corollary to the foregoing discussion, it is clear that the duty of water to be provided for in any locality is proportional to the evaporation-rate. On this basis, the high duty of water maintained in the San Bernardino Valley, in southern California, 7 or 8 acres per miner's inch, is no more creditable than the duty in Salt River Valley, Arizona, where for the last 3 years, the average duty of water, delivered, has been 5.4 acres per miner's inch. Following the over-use of water in many localities where it is abundant, some irrigationists now go to the other extreme, and advocate an impossibly high duty in the most desert valleys. Investigations relating to duty of water should be accompanied always by current observations of the evaporation rate, so that the results, when published, may be of more than local value. This precaution for making the investigations of wide interest has seldom been exercised.

A Principle of Ground-Water Hydrology.

That the ground-waters in arid valleys are not cumulative, is a principle which needs additional emphasis. Although there is a continuous movement of ground-water longitudinally in a valley, yet, in the main, the ground-water of one region does not get down into the next region. In this respect there is a close analogy between surface flows and underflows. Fig. 13 is a diagrammatic map of the Santa Cruz River and its principal tributaries. The widths of the lines are roughly proportional to the widths of the river channels, and indicate the regimen of the floods—the narrow torrents of the mountain canyons, and the spreading out over sandy beds and rapid absorption by percolation after leaving the canyon mouths. Normally, the river beds are dry. Many floods of the head-waters do not reach Calabasas, and few floods which pass Calabasas reach Tucson. The river is ever a dwindling stream, and, though draining greater areas, brings less water and smaller floods to the junctions with some of its tributaries than do those tributaries. Finally, at a point about 10 miles beyond the limit of the map, the channel is narrowed down to a width of 12 ft., and 2 miles farther on it entirely fades out. Likewise, the ground-water movements are represented by the same map. These movements are most active where the river beds are widest, where the recharging occurs; but at all points along the stream courses the moving ground-water is sustaining a loss, due mostly to transpiration, and the loss in any region is commensurate to the recharge in that region. The factors of recharge, loss, and forward movement are closely interrelated, though of varying importance in different localities within a region in their effects on the ground-water supply.

A logical sequence of these conditions is that extensive concentrated ground-water development is impossible. Vast areas of fertile land that could be reached easily by canals will ever remain desolate, but there are hundreds of small areas, usually stretching along the river courses, capable of reclamation by the utilization of ground-waters. The best of these small projects are to be found farther up stream. "The mountain water will not come down into the desert very far; we must go toward the mountain. The water must be used as near as possible to its source."* Mr. Smith.

Another sequence of the foregoing principle is that new diversions of ground-water in arid valleys are not so prejudicial to older rights as has been assumed oftentimes, and the doctrine of priority now applied to underflow streams of a definite character needs modification. In a discussion of the application of the doctrine to underflow gravity ditches,† the writer has suggested four points of limitation. They might well be applied to pumping operations also. The limitations relate to the burden of proof, to the extent of the injury, to co-operation in development work, and to the efficiency of the collecting agencies. Another consideration is that active interference between underflow ditches or between wells does not begin at once, but may require many months of lowering water plane, and, before the time has elapsed, one big flood may refill the gravels, whereupon all effects of the previous drafts on the ground-water supply are obliterated.

Estimates of Safe Yield.

The large items of the author's estimates carry much conviction as to their accuracy. Some of the small items, however, possibly need additional study.

1.—Percolation from Precipitation on Intermediate Mountain Slopes.—The Sierra slopes are said to be of unfissured granite covered by a mantle of loose rock. Table 16 gives the average annual rainfall as 12 to 20 in., derived mainly from the slow rains and snows of winter. Similar conditions exist on the slopes of the Catalina and Rincon Mountains, near Tucson, but observation indicates that most of the precipitation is absorbed by the porous overburden, wherein it supports an extensive desert vegetation. There is, of course, a slow creeping of the water downward at times, but very little of it reaches the valley. There are springs at the base of the slopes, but they are small, more suitable to be measured in cattle drinks than in second-feet. The run-off factors used for the intermediate mountain slopes of Owens Valley appear to be too high.

2.—The Upper Seeley Spring.—The location of this spring, at the north base of Charlies Butte, raises a question as to the derivation of

* *Proceedings*, 16th National Irrigation Congress, 1908, p. 206.

† 22d Annual Report, Arizona Agricultural Experiment Station, 1911, p. 570.

Mr. Smith. its water. If it is lateral flow from the outwash slopes, it is included rightly in the summary of ground-water losses, but if it is river underflow brought to the surface by the intervention of the butte—a hydrologic condition of common occurrence in the Southwest—then it should be omitted from consideration.

3.—It is stated that on the outskirts of the salt grass there is a strip of greasewood and bunch grass, that bordering this there is another zone of luxuriant sagebrush, and that the depth to water beneath these areas is from 8 to 20 ft. In the light of the foregoing discussion on transpiration, it is evident that the water loss from these bordering zones is of so much importance that an effort should be made to measure or estimate it.

4.—Another question of doubt to the writer is whether the underflow at Alabama Hills can be disregarded. The river bottoms here are 3 miles wide, and the rock trough is shown to be at least 832 ft. deep. The slope of the water-table is 8 ft. per mile. Although the valley fill on the Inyo Mountain side is composed of fine sand, yet on the opposite side there may be strata of good water-bearing gravels deposited by living rivers from the Sierra Range. A forward movement of the underflow of 6 in. a day throughout the section implies an item of loss of more than 20 sec-ft. This problem gives the writer more concern because in the arid Arizona valleys the bottom-lands do have usually some good water-bearing gravels. Thus, in the Santa Cruz "narrows", opposite Sentinel Hill, at Tucson, the underflow in the first water stratum must have been at least 10 sec-ft. before the recent development was made. The underflow loss can be measured or estimated by the Slichter method, and should be included in the balance sheet. Perhaps a fair estimate for Owens Valley is that the underflow gain at the north end of the Independence Region equals the underflow loss at the Alabama Hills.

In contrast with the author's orderly estimates are the crude methods which have found favor heretofore. A recent report on ground-water resources in an Arizona valley is based on absurd hypotheses, yet, on account of its authorship, the report ought to have been final and conclusive. The report first recites the water-shed area and rainfall, then applies Newell's run-off curves (which give values too high for arid regions), then deducts surface run-off, the quantity already applied to irrigation, and an allowance for evaporation from the dry river bed, and asserts that the remainder is underflow at the given cross-section of the valley. It ignores the largest factor of ground-water loss—transpiration—and assumes that the underflow is cumulative from the sources of the stream to the place under consideration. The magnitude of the underflow thus computed is excessively high, and is calculated to invite unwarranted expenditures in development.

On page 153 is the statement: Mr. Smith.

"There are * * * two possible methods of measuring the rate of recharge, either by determining the total percolation from various sources into the porous material of the basin, or by determining the ground-water losses."

The latter method is applicable in valleys where the loss areas are fairly compact and the vegetation fairly uniform; but, with a native vegetation of trees and shrubs, diverse in leaf expanse, in height, and in stand, and extending over irregular areas, there is little hope of approximating reliable estimates. On the other hand, as the recharge in very arid valleys is practically all from stream flows, the first method promises more accurate quantitative results. The essential features of the first method are an area survey and some gauging stations carefully selected, at the mouths of representative canyons, at the mouths of representative washes draining the outwash slopes, and near the outlet of the region. Fluctuations in wells, and water contour maps, present excellent qualitative studies, inasmuch as they reveal the direction of ground-water movements, the localities of active recharge, and the areas of loss. The first method has the disadvantage of requiring more attention to the residual losses in determining the safe yield than does the second.

The author has not discussed the probable variations in safe yield from year to year, though this is of great importance. Unfortunately, years of high rainfall, and again lean years, come in long series with great perversity. Rainfall records at Tucson show 6 years, from 1899 to 1904, with less than 10 in. of rain each year, followed by 5 good years with more than 10 in. each year, since which time there have been 4 years with rainfall below the average. The discharge from Sabino Canyon has varied from 2 900 to 46 100 acre-ft. per year. Ground-water levels respond more or less quickly to the variations in rainfall, and in some localities fluctuate over a wide range. Thus, along a section of Pinal Creek, the water-table has been as high as 12 ft. and as low as 85 ft. from the surface. The recent introduction of pump irrigation along the creek will increase the range of fluctuation.

Investigations of safe yield are most fortunate if made during a period when the rainfall is normal. In any case, the investigations should extend over several years, so as to eliminate the effects of storage from year to year. If data on the position of the water-table at many places can be secured during the year for which the estimates are made, the increase or decrease in the storage supply can be computed, and should appear as one item in the balance sheet.

Ground-water reservoirs of large capacity are better equalizers of the water supply than are surface reservoirs, but those of small capacity may be poor equalizers. In nearly all cases the highest utilization of ground-water requires the recognition of the principle of

Mr. Smith. fluctuating area under cultivation. Farmers are loath to admit the necessity for fluctuating area; the principle is not ideal, but in time it will be adopted by Courts and otherwise.

The author's summary of residual losses applies to many valleys perfectly. The outlet loss is not a loss to the State, however, inasmuch as it becomes available in the next valley region. What is termed the Artesian loss is, in many cases, not truly Artesian in character. This loss and the springs' loss are preventable by pumping operations. The loss by transpiration through trees is preventable, also, inasmuch as the feasible pumping lift is much greater than the limit of penetration of tree roots. Developments of the last 3 years in pumping machinery have doubled the economical limit for depth of pumping. Defining the efficiency of ground-water reservoirs as the ratio of the quantity recovered for irrigation to the total recharge, it is fair to anticipate, and to design works for, an exceedingly high efficiency, higher than many surface reservoirs, which lose from 3 to 10% through evaporation and an equal quantity through losses from a long supply canal.

Methods of increasing the safe yield require some variation from those proposed, in order to make them applicable to conditions in very arid valleys. Efforts to bring about greater absorption of flood-waters are not needed. The floods are wholly absorbed now, except for an occasional season of high rainfall, occurring perhaps once in 15 years. The efficiency of absorption through stream beds must be higher than that of absorption on an exposed slope. The only promising method is the elimination of transpiration through the denudation of the bottom-lands. The native forests and scattered trees should be removed, and, so far as the water supply permits, replaced by vegetation that is useful to man.

In conclusion, the investigations in Owens Valley are timely, for the extensive development of ground-waters in the Southwest points already to the over-draft, and in some places to the exhaustion, of the supply within a few years. The Engineering Profession, and not the Courts of Law, should take the prominent part in the final adjustment of pumping operations to the limiting physical conditions.

Mr. Meinzer. O. E. Meinzer, Esq.* (by letter).—Mr. Lee's investigation in Owens Valley is a valuable contribution to the study of ground-water. The demand for irrigation supplies and the increasing availability of ground-water because of improved irrigation and cultural methods and decreased pumping costs have created a need for information as to the magnitude of ground-water supplies, the question being primarily not as to the quantity stored in the earth but as to the annual recharge or safe yield. Any contribution to the methods for estimating the

* In Charge, Ground-Water Div., Water Resources Branch, U. S. Geological Survey, Washington, D. C.

annual supplies of ground-water, therefore, is especially valuable at this time. Four principal methods or groups of methods, which may be called the percolation, underflow, water-level, and evaporation methods, have been used. The first consists in estimating the quantity of water that percolates into an underground reservoir from streams or other surface sources; the second in measuring the flow of ground-water at selected cross-sections, being similar in principle to the gauging of surface streams; the third in observing fluctuations in the water-table, which represent filling or emptying of the underground reservoir; and the fourth in measuring the discharge of ground-water through evaporation from soil and plants. All these methods are laborious and difficult to apply, and none of them can be expected to produce precise results, but they are valuable, nevertheless, because they give some tangible basis for estimating ground-water supplies. In the Owens Valley investigation, Mr. Lee used both percolation and evaporation methods, his distinctive contribution consisting in developing the latter method and placing it on a quantitative basis. Mr. Meinzer.

The evaporation method gives promise of extensive applicability because a large number of the ground-water reservoirs that will be developed for irrigation discharge wholly or chiefly by evaporation. Débris-filled basins are the most characteristic features of the United States west of the Rocky Mountains. They are of two types: Those which discharge ground-water through springs and evaporation areas, as described by Mr. Lee, and those which do not. In the geologic literature dealing with these basins this fundamental distinction is generally ignored, and the characteristics of the evaporation areas are commonly accounted for by the wholly inadequate explanation of evaporation of surface waters. The process of ground-water evaporation, however, has been clearly stated by F. H. Newell,* M. Am. Soc. C. E., in one of the earliest papers on water resources published by the United States Geological Survey, and in recent ground-water investigations the significance of evaporation areas has come to be clearly recognized. Mr. Lee has furnished experimental data showing that these areas are quantitatively important in discharging ground-water.

Work in numerous débris-filled basins has shown that it is entirely feasible to ascertain from surface indications whether or not a basin is discharging ground-water by evaporation. The evaporation areas in some of the basins have been mapped with nearly the same accuracy that is possible in mapping geologic formations. The three criteria, all of which are suggested in the paper, are (1) moisture of the soil; (2) soluble salts at the surface; and (3) native plants that feed on ground-water. Experience is necessary, of course, for a proper application of these criteria, but they are trustworthy when rightly used. Moreover, they can be tested at any time by making a shallow boring,

* "Water Supply for Irrigation," U. S. Geol. Survey, 13th Annual Rept., 1893. Pt. 3, p. 29.

Mr. Meinzer. for ground-water evaporation takes place only where the water-table is near the surface. In a recent ground-water survey of the Big Smoky Valley, Nevada, the relations between the vegetation zones and the depth to the water-table were found to be very similar to those stated by Mr. Lee (page 198), but the plant species that serve as indicators of ground-water are not the same in different parts of the West. The mapping of evaporation areas is important, not only because these areas make possible estimates of the annual supplies, but also because they reveal the base level of the ground-water surface, and thus make possible a forecast of the depth to water in other parts of the basins in which they occur.

Mr. Lee's first conclusion (page 149) is open to criticism in being too general. On the basis of his investigation in the Owens Valley, he concludes that the underground reservoirs of California and the Southwest are water-tight rock basins. Many of the débris-filled basins of the Southwest, however, even those comparatively well enclosed by mountains, have no ground-water discharge through springs, evaporation, or transpiration, and it must be assumed that the supplies which they undoubtedly receive are disposed of entirely through rock absorption or underground channels of escape. Some of the reservoirs which discharge water by springs, soil evaporation, and transpiration, no doubt also suffer losses through rock absorption or leakage. In this respect each basin forms a separate problem, the amount of underground loss depending on the stratigraphy and structure as well as the topography. It should be noted that such loss, if heavy, will make the estimates obtained by the percolation method too large and may make those obtained by the evaporation method too small. One of the sources of the public supply of Goldfield, Nev., has consisted of wells in a closed débris-filled basin which has no discharge by evaporation. Such a basin will yield some water even though it has no natural discharge through springs, evaporation, and transpiration, but its yield will be less than the quantity that percolates from surface sources to the water-table.

The writer was disappointed in not finding in Mr. Lee's paper a more definite discussion of the probable percentage of accuracy of his results, as such a discussion would have added greatly to the value of the paper. Mr. Lee's analyses both of recharge and of loss are excellent, but in order to reach quantitative conclusions he was obliged to make numerous assumptions in respect to both. Although these assumptions were, the writer believes, made carefully and with good judgment, they must have introduced considerable errors into the computations. As assumptions enter into both estimates, neither one can be regarded as a check on the other. The fact that the two estimates are of the same magnitude justifies added confidence in the general results, but the fact that they differ by less than 4% does not indicate, of course,

Mr. Meinzer.

that the percentage of error is within 4%, and can hardly be considered a confirmation of the reliability of the data and the correctness of the assumptions in either computation (page 212).

The four sources of percolation are given as (1) direct precipitation; (2) stream flow; (3) irrigation; and (4) flood-water in the valley floor. It is assumed that the high mountain areas shed all precipitation except that which is lost by evaporation; that on the more elevated parts of the intermediate mountain slope 75% of the precipitation, and on the lower parts 70, 65, and 60%, respectively, join the underground supply; that the contributions to the underground supply on the outwash slopes range, according to zones, from 0 to 60%, making an average of 16%; and that the contribution on the valley floor is 4 sec-ft. All these assumptions are based on careful, general observations, but are of course only approximations and subject to large errors. Moreover, assumptions are involved as to the areas belonging to the various zones and the amount of precipitation in each (page 206). Several assumptions are also made in the estimate of recharge from stream channels, in the conclusion that 50% of the irrigation water is added to the underground supply, and in the estimate of the contributions made by the flood-waters.

The writer agrees with Mr. Lee that the discharge from the underground reservoir can be determined more accurately than the percolation into it, but the methods of estimating discharge also involve a number of elements of uncertainty. If the writer understands rightly the author's discussion of the discharge from irrigated land, the 50%, or 18 sec-ft., of irrigation water discharged by evaporation and transpiration (page 203) is the portion that was not added to the underground supply (page 212) and, therefore, should not be included with the discharge from this supply.

The largest element in ground-water discharge is that of evaporation and transpiration from uncultivated land. It is on this question that Mr. Lee has made his most important contribution, and that part of his paper dealing with this phase of the subject deserves, therefore, the most critical consideration. Some of the factors that enter into this estimate were determined by experiment and others by field survey. Experimental errors were involved in the difference between natural and artificially packed soils, in the difference between the vegetation in Nature and in soil tanks (pages 186, 187, 192, and 193), in uncertainties as to the actual water-level in the tanks (pages 183 and 184), and in the unavoidable fluctuations in the water-levels in each tank (Tables 9 to 14, inclusive). These experimental errors are represented in part only in the diagrams in Fig. 10. In the summer diagram, which is the more important one, the results from Tanks Nos. 5, 6, and 7 fall nearly on the curve used by Mr. Lee in his calculations, the result from Tank No. 4 being more than 20%

Mr. Meinzer. too low, that of Tank No. 3 more than 20% too high, and that of Tank No. 2 nearly 40% too low. It should be noted, however, that although these results involve large experimental errors, they corroborate each other in a general way and are of great value in furnishing reliable data on the general magnitude of one of the most important processes in ground-water circulation.

In applying the experimental data to the basin under investigation, inaccuracies were involved in the sizes of the areas having specified depths to the water-table, in the fluctuations of the water-table, in difference in the range and rate of capillary rise due to difference in the character of the soil, and in difference in the density of vegetation and kinds of plants that draw water from the underground reservoir. An error was also involved in the fact that observations covering only 1, 2, or 3 years did not give average evaporation conditions, just as precipitation and stream-gauging data for a period of the same length do not afford reliable averages. With 142 observation wells on the valley floor (page 197), the error as to the water-table cannot have been large, yet the rate of discharge varies so greatly with small changes in depth of the water-table that even slight inaccuracies in determining one produce appreciable errors in calculating the other. Although the valley floor in that part of Owens Valley investigated by Mr. Lee has relatively uniform conditions, there is luxuriant salt grass in some parts and an entire absence of vegetation in others (page 161), whereas the experiments did not cover these different conditions. Moreover, no account was taken of the zone having depths to the water-table between 8 and 12 ft., although the greasewood and rabbit brush in this zone probably draw water from the underground reservoir (page 198).

The writer agrees with Mr. Lee that the evaporation method is the most feasible one for estimating ground-water recharge in many of the débris-filled basins, especially where there are as yet few developments, but its application is far from being a simple matter. The data which he obtained in Owens Valley have value in making rough estimates of annual recharge in valleys in which the evaporation areas are mapped and reliable observations are made as to the character of the soil and vegetation and the distance to the water-table in the different zones of such areas, but to assure any considerable degree of accuracy for most valleys it will be necessary not only to sink a large number of observation wells and to keep them under observation for one or more years, as was done in Owens Valley, but also to obtain a great deal more information as to the rate of discharge under various conditions of soil and vegetation. The conditions in the evaporation areas of most valleys are far from uniform, the soil ranging from dense clay to coarse sand or gravel, and the vegetation embracing a number of diverse species and being entirely absent over large tracts.

The writer wishes to urge the importance of further investigations along the lines suggested. The lowest parts of many of the closed basins are underlaid by clay cores destitute of vegetation but surrounded by zones of less dense soil in which evaporation and transpiration are active. The dissemination of the soluble salts instead of their concentration at the surface and other conditions lead him to believe that on these clay cores the ground-water discharge is sluggish, but definite tests are needed as to the quantity of discharge and its relation to the distribution of the soluble salts. Among the common native plants (besides the salt grasses) which apparently discharge ground-water, are samphire (*Spirostachys occidentalis*), iodine weed (*Suaeda*), alkaline sacaton (*Sporobolus airoides*), certain species of salt bush (*Atriplex*), big greasewood (*Sarcobatus vermiculatus*), rabbit brush (*Chrysothamnus graveolens*), buffalo berry bush (*Shepherdia*), and mesquite (*Prosopis*). Mesquite does not thrive in the shallow-water areas where the soil is dense and alkaline, but is often dominant in a zone of moderate depth to water surrounding a shallow-water area. It is important to know whether the mesquite actually feeds on ground-water, and if so, from what depth and at what rate it is able to lift this water to the surface. Mr. Meinzer.

Mr. Lee's final conclusions (page 218) sum up admirably the esssential factors in the problem of safe yield. As it is not generally practicable to draw any large part of the ground-water of one segment of a valley to another, a proper distribution of wells is necessary in order to reduce the residual losses to the lowest possible quantity. Overdraft with serious lowering of the water-table may occur in certain segments while evaporation of ground-water contributed by other segments is still in progress on the lowest lands. Such loss can be prevented only by increased withdrawals in the undeveloped segments, and if these segments have little or no land that can be profitably irrigated, the loss may be unavoidable.

Kenneth Allen,* M. Am. Soc. C. E. (by letter).—Underground water supplies, as well as surface supplies, depend on the rainfall, the catchment area, and the available storage, with its accompanying losses by overflow, leakage, and evaporation; but the problem for the engineer is more difficult in the case of underground supplies, as the true limits of the catchment area, the storage capacity, and the probable amount of the losses mentioned can only be determined approximately after a pretty thorough examination of the sub-surface conditions, that is, the configuration of the permeable strata, their impermeable confines, and their physical characteristics—permeability, etc. In the majority of cases much of this information is inaccessible, and more or less dependence is placed on such collateral evidence as the yield of neighboring wells and the results obtained by sinking test wells. Mr. Allen.

* New York City.

Mr. Allen.

The limitations imposed by enclosing impervious formations and by sub-surface evaporation are clearly and interestingly presented by the author, and their importance is shown under the conditions discussed. In most well developments, however, evaporation is of minor significance. This is not only on account of greater humidity, but because most supplies percolate through an unenclosed stratum for perhaps many miles and because evaporation from this stratum is usually prevented by the superposition of one or more impervious strata.

In practice the available yield is subject to further limitations. The water-bearing stratum may consist of an impervious rock containing crevices or fissures due to movements in the earth's crust, or water-courses caused by the solvent action of the water itself. The latter are of frequent occurrence in limestone and chalk formations and the former in sandstones and the denser igneous rocks. Fissures occur more frequently near the surface than at great depths, and, as the cost of drilling increases with the depth, deep borings in search of water-bearing fissures are not often profitable. The same money can be spent to better advantage in making several test borings at moderate depth. Although the results of such borings are uncertain, supplies, when obtained from fissures, are often abundant and the wells free from the clogging so often experienced with sand. The yield of a well in sand is directly limited by the porosity of the latter and the available head. In fine sands there is a large loss of head due to percolation near the strainer in order to maintain the necessary flow. This difficulty may be overcome by increasing the length of the strainer, if this does not exceed the thickness of the water-bearing stratum, but this is at the expense of a greater first cost as well as an increase in lift due to the fineness of the material. In such cases the loss of head is often reduced by removing the sand about the strainer and filling the pocket with gravel, or else by substituting a larger number of driven well points from 2 to 3 in. in diameter for the large (6 to 12-in.) casing and strainer.

In those cases where the water occurs in a stratum of fine sand of small thickness, the difficulty is further increased. The writer tested a stratum of this kind several years ago with the view of developing a supply of some 5 000 000 gal. daily for a southern city. Water was found in apparent abundance throughout a large area at a moderate depth, the land was low, covered with forest, not far from a stream of considerable size, and on it were several large springs. On sinking numerous test wells on a line about 4 miles long, however, it was shown that the water-bearing stratum, besides being of a fine sand, was so thin that the cost of developing the desired supply would be prohibitive.

Water supplies found in deep deposits of sand or drift, especially those derived from distant and extensive catchment areas, such as

Mr. Allen.

exist south of the great terminal moraine on the south side of Long Island and on the Atlantic Coastal Plain from Sandy Hook to Florida, are most favorable for development. Well-known examples are the 1 400-ft. Ponce de Leon well at St. Augustine, said to furnish 10 000 000 gal. daily, and the 1 970-ft. well at Charleston, furnishing 1 250 000 gal. daily. On the other hand, a well was bored in 1900-01 at Atlantic City, N. J., to a depth of 2 306 ft. (below the floor of Young's Pier), and although a good supply was found between depths of 780 and 860 ft., in a stratum of sand tapped by numerous wells in the vicinity, the supply sought at the greater depth was not realized, and the well, then the deepest but one along the Atlantic Coast, was abandoned.

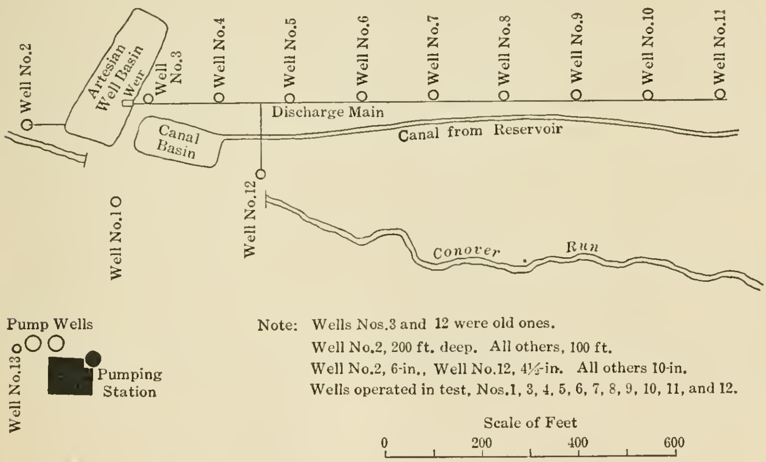


FIG. 15.

About 5 miles inland, the Water Department had a small collecting basin near its pumping station (Fig. 15), in which were driven a number of 4-in. tubes tapping a water-bearing stratum 24 ft. below. Near the basin was a 10-in. well (No. 3) extending to a depth of about 100 ft. to another water-bearing stratum which it was proposed to develop as an additional supply to the extent of 3 000 000 or 4 000 000 gal. daily. The capacity of this well was first tested by erecting over it an old 1 000 000-gal. Worthington pump, which the Department had, and connecting it with a steam line to the boiler plant at the station. During a 6-hour test with a 19-in. vacuum on the suction, the delivery was practically uniform at a rate of 840 000 gal. per day, and as no downward flow was observed in the small tubes in the basin, it was concluded that there was no connection between these two strata. On the strength of this test, ten 10-in. wells, 125 ft. apart, were sunk to a depth of about 100 ft. and a 6-in. well (No. 2) to a still deeper

Mr. Allen. stratum, 200 ft. below the surface. Besides these there were two old wells—the 10-in. well tested with the steam pump and a 4½-in. well (No. 12), both of which were carried to the 100-ft. stratum. The deeper 6-in. well flowed freely at a rate of 66 000 gal. per day and, by use of the air lift, at a rate of 400 000 gal. per day, or about 280 gal. per min. The 10-in. wells on short separate tests produced from 150 to 400 gal. per min. Ten of the 10-in. wells (No. 1 and Nos. 3-11) and the 4½-in. well (No. 12) were then connected with the compressor and given a 6-hour test. These wells together delivered 846 879 gal., or at a rate of 3 705 492 gal. per day. This was an average of 336 866 gal. per well, or 60% less than the delivery from Well No. 3 when operated alone. Moreover, the average lift in this well during the test was 24.56 ft., though the vacuum gauge on the suction during the earlier separate test indicated a lift of 21 ft. to about the same level. Assuming this well to have produced one-eleventh of the total quantity during the combined test, the effect of interference from the other wells, while operating all eleven at this rate, was to increase the lift by about 3.6 ft. while reducing the output by 60 per cent.

The yield under conditions found along the Coastal Plain region bears little relation to that from underground reservoirs of the closed-basin type described by the author, but somewhat similar conditions are met in the basin of the prehistoric Lake Passaic of Northern New Jersey. Wells in the outlet of this lake, now filled with glacial drift, furnish the water supply for East Orange. When first sunk, several of these 6-in. and 8-in. wells had a natural flow of from 400 to 500 gal. per min.

Above this outlet water-bearing sandstones underlie the ancient lake, but percolation to these beds is cut off on the northwest by the trap dikes forming the Orange or Wachung Mountains and on the southeast by the Palisades of the Hudson. Assuming a general southerly flow, percolation from a distance, therefore, is limited to that from the northeast, the limit in this direction, it is believed, being unknown.

These sandstones, nevertheless, furnish a large number of excellent well supplies in the vicinity of Newark and Paterson, chiefly by means of their numerous fissures.*

Data concerning a large number of these wells, collected by the writer a few years ago, indicate a great variation in the yield. They are commonly from 100 to 500 ft. in depth, and 6 or 8 in. in diameter, and generally furnish from 20 to 200 gal. per min. each, although failures are not infrequent, and several produce as much as 500 gal. per min.

* Report, State Geologist of New Jersey, 1903, p. 79; also Water Supply and Irrigation Papers, U. S. Geological Survey, No. 114, p. 96.

Mr. Horton.

ROBERT E. HORTON,* M. AM. SOC. C. E. (by letter).—This paper bears abundant evidence of being the work of an accomplished hydrologist, and specially commends itself to the writer because it represents the combined application of studies of the rainfall and run-off relations of the basin itself with laboratory experiments on evaporation losses.

For many purposes in hydrologic work, laboratory experiments are capable of yielding very instructive results because the problems in Nature are often so complex as to make it difficult to separate effects produced by one cause from those produced by a combination of causes. After studying the completed results, various ways suggest themselves by which the experimental data might have been improved. The writer, however, refrains from criticism in this regard, fully realizing how difficult it is at the outset to determine the best lines or methods of investigation and how to prepare in advance for conditions which may arise unexpectedly in the progress of the work.

The paramount problem in applied hydrology is the utilization of existing data for a locality, whatever the data may be, and whether complete or incomplete, so as to derive therefrom the best possible solution of the specific problem.

The writer feels that Mr. Lee's work in the acquisition of data has been somewhat in advance of his analysis of the results, in that the work of other experimenters on the question of soil evaporation, and transpiration in particular, might have been analyzed and to some extent utilized to advantage in this case. For example, it would seem that the difficulties experienced in obtaining constant ground-water table in the soil evaporameters should have been foreseen. Quite similar experiments were carried out successfully by Ebermayer many years ago, using the apparatus shown in Fig. 16, in which the lower surface of the soil prism is maintained constantly in contact with the water surface by an automatic air valve in the reservoir, *C*. The uplifting of water from the soil prism is entirely the result of capillary action.†

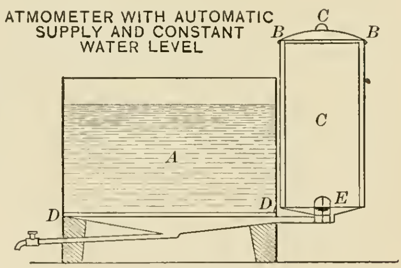


FIG. 16.

The writer has not had opportunity to examine Water Supply Paper No. 294, which presumably contains detailed results of the observations of precipitation and run-off. It would have added to the value and interest of the paper if Mr. Lee had included tables

* Albany, N. Y.

† A full description of Ebermayer's experiments and results is given in a paper by the writer in *The Michigan Engineer*, 1913-14, pp. 66-89.

Mr. Horton. showing the monthly precipitation and run-off of the different streams, because it is unusual to find records of the attendant conditions available in conjunction with stream flow data, as is the case here.

Mr. Lee states that the flow of the mountain gulch streams tributary to Owens Valley is practically constant throughout the frozen season. This statement is only relatively true. From the data relating to these streams appearing in Water Supply Paper No. 300, their yield varies 100% or even more, there being generally a gradual decrease in flow from the beginning to the end of the frozen season. Attention is called to this point principally because a fundamental principle of the regimen of streams is commonly overlooked, namely, that a stream or spring cannot yield a constant outflow throughout any considerable period of time unless there are simultaneous additions to the available water supply. In the case of the mountain streams in question, the winter precipitation occurs as snow and remains frozen generally throughout that period, thus eliminating any increment of supply to the streams from surface water. Presumably there is a ground-water reservoir from which these streams are gradually fed throughout the winter. This ground-water reservoir must of necessity be gradually depleted and the flow of the streams gradually decreased, as appears to be the case. This, however, brings up an interesting problem. It appears possible, and indeed probable, that in many instances waters which have previously entered the soil but remain above the zone of saturation—or, in other words, above the ground-water table tributary to the stream—gradually percolate downward, entering the body of ground-water and aiding to maintain a constant supply through long periods of drought or during the winter when surface supply and infiltration are shut off. If the rate of addition to the ground-water body is greater than the initial rate of outflow therefrom, the ground-water table will gradually rise to such a height that the outflow will become equal to the inflow from percolation, and then, as long as the downward percolation remains substantially constant, the yield of the stream also will remain constant.

Mr. Lee's paper brings out forcibly an important hydrologic fact often overlooked, namely, that very substantial yields of water may often be obtained permanently from undrained depressions or closed basins where naturally the entire precipitation is lost through evaporation. To accomplish this it is only necessary to reduce the evaporation as much as possible below the inflow from precipitation. This, as pointed out in the paper, will naturally result if the ground-water table is drawn down permanently below the limit of capillary uplift and evaporation from the soil, and below the limit of absorption by plant roots.

Mr. Horton.

Mr. Lee describes the typical geological construction of a mountain fault basin as the result of the product of faulting accompanied by the uptilting of a crustal block from one side of the line of fracture. Fault valleys of this type are not uncommon in the East. One of these, in the eastern slope of the Helderbergs, not far from Albany, is known to the writer. In this case a section of the valley is apparently somewhat as shown in Fig. 17. It appears to the writer probable that in this case, and no doubt frequently in other cases, there are more or less débris-filled spaces, *A* and *B*, between the ends of the tilted blocks and the fault face. As a result, there are likely to be subterranean outlets from the valley through the spaces, *A* and *B*, at greater or less depths below the junction of the valley surface rock with the fault face at *C*. In the vicinity referred to, frequent illustrations of tilting and overthrust of underlying strata can be seen. Evidence of subterranean channels along the fault line beneath the rock floor of the valley appears from the fact that the only visible outlet of drainage from the valley is through a very large and permanent spring which comes to the surface along a continuation of the fault line at a distance of about a mile from the lower end of the valley and at the point where the fault line crosses the valley of a large stream.

FAULT IN MOUNTAIN VALLEY FORMATION

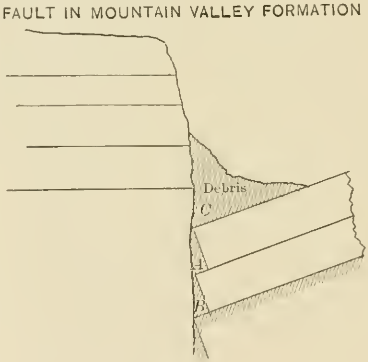


FIG. 17.

This instance, and the frequent occurrence of undrained depressions in the East, suggests to the writer the fact that the underlying principles of hydrology are very general, and the conditions widely distributed throughout the earth. Unfortunately, the range of conditions is not as well recognized as it should be, and it is probably due to this fact, rather than to differences in the classes of conditions to be met, as classes, that there have been so many wild and erroneous estimates of the available yield of water supplies. In view of the limited experiments and studies which have been made along scientific lines such as those carried out, for example, by Mr. Lee, for the solution of specific problems, it becomes an increasing matter of wonderment to the writer that serious mistakes and miscalculations in the available water supply for municipalities or for power or other purposes have not more often been made.

It is often the case that the success or failure of a hydraulic project depends primarily on the water supply, yet, as a rule, much less attention is given to the scientific determination of this element

Mr. Horton. than to many much less important structural elements. The writer is pleased to see in the present instance the hydrologic side of the question at issue given apparently its due share of attention.

The writer feels obliged to take exception to Mr. Lee's statement that the transpiration from plants is independent of the humidity. The elegant experiments along this line by Ganung, in connection with which graphic records of transpiration and of the accompanying meteorological elements, light, humidity, and temperature, were obtained, illustrate quite conclusively, it would seem, that there is a fairly definite relation between transpiration rate and humidity.*

Mr. Lee has proved that the increase in rainfall on mountain slopes is more nearly proportional to the slope gradient than to the absolute humidity. It seems necessary to call attention to the distinction between the increase in atmospheric precipitation which, as shown by the classic researches of Pockels, is directly the result of dynamic cooling and consequently is a function of the elevation of a mass of air, nearly or quite independent of its horizontal transportation in the meantime, on the one hand, and the increase in precipitation on the ground surface, on the other hand. The difference is illustrated by Fig. 18. Consider two masses of air of equal volume, M and N, respectively, approaching the slopes AB and CD.

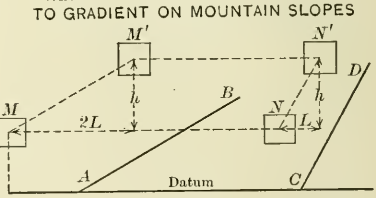


Fig. 18.

Let both masses be initially at the same height, and let both be elevated throughout the same height, h, to the positions, M' and N'. The same quantity of precipitation will be produced from each mass of air. If the gradient, CD, is twice as steep as the gradient, AB, the resulting precipitation on the flat slope, AB, will be distributed over twice as great an area as that on the slope, CD, as is evident from the diagram. Thus the apparent increase in precipitation will be proportional to the slope gradient.

The peculiar condition existing in the case of triangular mountain drainage areas, whereby the mean precipitation occurs at the center of area of the drainage basin, illustrates the importance of weighting rainfall records, taken at different portions of a drainage basin, in proportion to the relative part of the total area which each one represents. This practice has been followed by the writer for a number of years in estimating mean rainfall on drainage areas. The necessity for the use of such a process arises partly from the fact that rainfall stations are most commonly located in stream valleys. In the case of triangular basins, similar to those tributary to Owens Valley, but

* "The Living Plant," by W. F. Ganung, p. 204.

for the extreme condition of zero precipitation at the mouth of the stream, the average of a line of equidistant rainfall stations located along the stream from its source to its mouth, would give an apparent mean precipitation for the area only five-sixths as great as the true mean precipitation, or the error would be $16\frac{2}{3}\%$ of the true mean. Mr. Horton.

Mr. Lee.

Charles H. Lee,* Assoc. M. Am. Soc. C. E. (by letter).—Realizing the somewhat local character of his paper, the writer has been highly gratified to find that it has brought forth discussion based on such widely divergent as well as similar experience. He especially appreciates the broad and constructive contributions of Messrs. Smith and Meinzer, whose wide experience with ground-water problems qualifies them to speak with authority.

The writer heartily agrees with Mr. Owen that there is a great need in all sections of the United States for definite scientific knowledge regarding the principles which should govern ground-water development. He would not, however, place such knowledge in the realm of the unattainable, as both Messrs. Owen and Allen in their opening paragraphs seem inclined to do. The Engineering Profession has already made considerable progress in the formulation and application of such principles. In Europe, for instance, where the demand for municipal water supplies has reached the point where the limit of every available source must be known, there has been accumulated such a fund of knowledge derived from investigation and experience that the subject is recognized as a distinct branch of the Profession. In the United States the exhaustive investigations of ground-water supply, such as that made on Long Island by the City of New York and the work of the United States Geological Survey, show that in America, also, the subject has advanced far beyond the stage of conjecture. It is the writer's opinion that the time is now ripe for the formulation of general principles and methods of investigation and development of ground-water among American engineers, and it was with this in view that his paper was written. It is to be hoped that similar papers will be presented by members of the Society who have had opportunity to study other types of ground-water occurrence, in order that a more complete presentation of the subject in its most recent development may become available to the Profession.

The writer was much interested in the statements of both Messrs. Smith and Meinzer that the term "water-tight" as applied to ground-water reservoirs is a relative one, and that, in many arid States, it does not apply at all. Their experience and the writer's more recent observations outside of California are in accord in this matter, and the first conclusion of the paper (page 149) should be modified accordingly. In all the California basins which have come under the writer's

* Los Angeles, Cal.

Mr. Lee. observation, however, the term can be used for all practical purposes. These basins occur either in granite or in tertiary sandstones and shales, and, as the fill is recent, the difficulty encountered by Mr. Smith in defining the basin seldom arises.

Both Messrs. Meinzer and Smith have commented on transpiration losses, and the latter has contributed the first really useful statement of basic principles which the writer has seen. It is to be hoped that further work will be done to confirm the principle of equal relative rates of transpiration, and that quantitative determination be made of the ratio between evaporation and transpiration. In all such experiments care should be taken to measure evaporation under some standard condition, for, as is well known, the results derived from pans in large bodies of water, in wet soil, in dry soil, and in air, differ widely, and in the same environment differ with atmospheric exposure.

In this connection the writer wishes to call attention to the fact that Mr. Smith's conclusion (page 226) that the combined loss by evaporation and transpiration from salt-grass sod is twice that from damp soil alone is not justified. The rate of water evaporation from the deep tank in the soil far exceeded that from soil during the winter, for the reason that the soil was kept cold by evaporation and cold air temperature, while the water was free to circulate and received warmth from the deeper soil. Experiments (which the writer carried on but did not publish) indicate that the annual evaporation from saturated base soil is about 93% of that from the water surface in the deep tank. The combined transpiration and soil evaporation for similar conditions was 115 per cent.

With these general observations the writer will pass on to detailed comments on the discussion of the paper. Mr. Smith's paragraphs, grouped under the head of "Estimates of Safe Yield" (pages 231-234), will be taken up first.

1. The conditions on the slopes of the Catalina and Rincon Mountains, described by Mr. Smith, are not as similar to those of the east slope of the Sierra Nevada as would appear at first glance. Table 3 shows that the lowest elevation of the Sierra slopes is 6 500 ft., the average 7 500 to 8 000 ft., and the maximum elevation 12 000 ft. The similar slopes back of Tucson extend from an elevation of 3 000 to about 6 000 ft. The Sierra slopes do not support a luxuriant desert vegetation nor forest growth, the latter, especially, being spotted and sparse. The precipitation on the Sierra slopes is all in the form of snow, which melts and sinks into the porous mantle before the growing season commences. On the intermediate slopes of the Catalina Mountains, however, the precipitation occurs largely in severe summer storms, from which the run-off is rapid and the percolation is immediately available to vegetation. These differences are all such as to favor greater percolation on the Sierra slope. Furthermore, there are

numerous springs at the base of the Sierra slopes, the flow of which, in many cases, can be measured in second-feet instead of cattle drinks. Hence, the writer still believes that the run-off coefficients used are not excessively high. Mr. Lee.

2. Charlies Butte is a low mound of lava near the margin of a shallow flow which advanced out over the valley-fill. The Butte is not the crest of a bed-rock projection, as Mr. Smith suggests, but is superimposed on the valley-fill. The spring is of the type described by the writer on page 175, and unquestionably has its source in percolation from the outwash slope.

3. The writer believes that Mr. Smith is justified in giving a value to transpiration from the luxuriant desert vegetation, the roots of which are within reach of the water-plane. The addition of this quantity would increase the computed ground-water discharge from the basin.

4. Relative to the matter of underflow from the basin past the Alabama Hills, the writer has given this matter considerable thought at various times, and cannot agree with Mr. Smith as to the probability of there being an appreciable loss at this point. For a distance of 6 miles from the "Point of the Hills" to Lone Pine Creek there are no lateral streams breaking through the hills. The whole cross-section was formerly covered by Owens Lake, and any material brought down by Hogback Creek would have been deposited on the lake shore at the "Point of the Hills", or, in case of low lake level, would have been carried directly out on the lake bed. There would be no condition favoring or even rendering possible the deposition in the section of any but the finest materials, even on the side adjoining the steep slope of the Alabama Hills. Further, there is the elevated water-plane of the Lone Pine delta opposing such underflow, and the absence of any evaporating area which would naturally result from the back-water effect. Finally, there is the fact that the valley floor of the Independence Basin above the Alabama Hills is an old lake bed beneath which fine sands and clays predominate, that the porous gravels of the outwash slope surround this relatively non-porous core, that ground-water percolating laterally through the gravels meets a barrier at the old lake shore and is compelled to seek an outlet locally by spring flow and evaporation, and that, therefore, the conditions necessary for an active underflow down stream are entirely lacking throughout the whole of the valley floor.

The discussion of probable annual variations in safe yield is not of such great importance for the Independence Basin as in other basins. This is due to two reasons, the immense storage capacity of the saturated gravels and the non-porous core or heart of the valley. The former is relatively very large with respect to any judiciously developed draft, and the latter holds up the water-plane and prevents the escape

Mr. Lee. of water from the basin by underflow. Thus, the fluctuation of the water-plane within a reasonable distance of the old lake shore would not be great, even in periods of extended drought. The effect of variations in ground-water supply in the Independence Basin would appear more as variation in spring flow and evaporation loss than as fluctuation in the water-plane.

Mr. Meinzer's long and intimate experience and scientific study of the problems involved in this paper make him one of the best qualified men in America to discuss it, and his contribution has added greatly to its value. The writer, however, feels that in general his discussion is from the point of view of the pure scientist who strives for absolute accuracy, rather than from that of the applied scientist or engineer whose aim is relative accuracy. There were involved in the solution of this particular problem not only questions of obtaining a proper internal balance in relative accuracy, but also that of giving the problem its proper place in the larger one of determining the safe yield from all sources available for a large municipal water-supply project. The quantity of ground-water available for development from the Independence Basin is about one-fifth of that available from all sources. The writer believes the results obtained, as set forth in this paper, are well within the limits of reasonable accuracy for the purpose desired. Considered in this light, he does not agree with Mr. Meinzer that the assumptions are "subject to large errors."

Considering Mr. Meinzer's discussion in detail, the writer is indebted to him for drawing attention to the erroneous inclusion with ground-water discharge of 18 sec-ft. of irrigation water dissipated by evaporation and transpiration. As has been pointed out by both Messrs. Smith and Meinzer, however, there is an appreciable loss from rank desert vegetation bordering the shallow ground-water area. The inclusion of this with ground-water losses would increase the latter, and, therefore, the corrections in the final result would tend to offset one another.

Mr. Meinzer states that observations covering 1, 2, or 3 years do not give average evaporation conditions, comparing them with precipitation and stream-gauging data in this respect. The writer does not believe that this statement would have been made if evaporation records covering several years had been examined. The range of annual variation in evaporation is usually less than 4%, whereas precipitation and stream flow may have extreme variations of more than 100 per cent.

Mr. Meinzer suggests that, in order to apply the results of the Owens Valley evaporation experiments to other valleys, it would be necessary to have a large number of observation wells and keep them under observation for several years. The writer's experience in other valleys during the past 3 years has been that water-plane fluctuations

in evaporation areas follow the same annual periodic law observed, and have about the same range as observed in Owens Valley. Hence the observation of a few judiciously chosen wells at a critical date, preferably late in September, should give dependable results. Mr. Lee.

The writer agrees heartily with Mr. Meinzer that further investigations of soil evaporation and transpiration under various conditions should be made. In connection with the rate of evaporation from bare alkaline lake beds or "playas", certain experiments recently carried on under the writer's direction tend to confirm Mr. Meinzer's observations. The evaporation from two pans of water under exactly similar conditions was observed, one pan containing distilled water and the other a sample of highly alkaline lake water. The rate of evaporation from the denser water was less than that from the fresh water, and rapidly decreased to a very small value as the salts began crystallizing out, regardless of the fact that no permanent crust was allowed to form.

The writer is very glad that Mr. Horton has emphasized the fact that in the development of hydrographic projects the most important feature, that is, water supply, is seldom given the adequate investigation that it requires. The writer has in mind several irrigation projects which are either partial or complete failures solely because insufficient study was made of the available water supply.

Although familiar with the work of the German experimenters on soil evaporation and transpiration which Mr. Horton cites, the writer found that the climatic and soil conditions under which their experiments were performed were quite different from those in Owens Valley, and that the experimental equipment did not reproduce as closely as seemed desirable the natural conditions. Hence, he found it impractical to follow their precedents as closely as would seem possible at first glance.

In comment on Mr. Horton's suggestion that tables of rainfall and run-off would have added to the value of the paper, the writer wishes to draw attention to Article VI, Section 11, of the Constitution of the Society, which contains the statement that "papers offered for presentation * * * containing matter readily found elsewhere * * * shall be rejected."

The writer takes exception to Mr. Horton's statement that there is no increment of flow during the frozen season to the mountain streams tributary to Owens Valley. Although it is true that the surface of the snow is frozen, yet on the under side, in contact with the soil, containing more or less stored heat, there is a slow but continual melting which contributes a permanent supply to stream flow all winter. This is proved by the observed fact that if freezing weather occurs before the first snowfall, the streams show material reduction in flow, but that, soon after the mountain slopes are snow-covered, there is a return to normal winter flow.

PLATE IV.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.

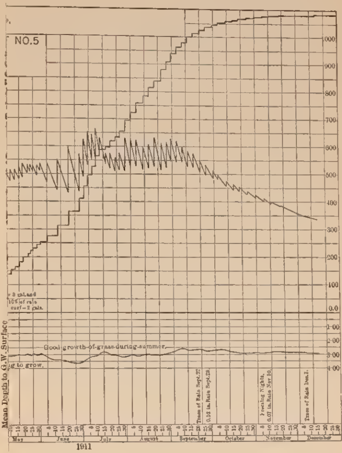


PLATE IV.
TRANS. AM. SOC. CIV. ENGRS.
VOL. LXXVIII, No. 1315.
LEE ON
YIELD OF UNDERGROUND RESERVOIRS.